Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

Design Management Model for Transformable Architectural Structures

Maziar ASEFI

Assistant Professor, School of Architecture, Tabriz Islamic Art University
Tabriz, Iran
asefi@liverpool.ac.uk

Abstract

The design of transformable architectural structures is difficult in comparison to static architectural structures. This is due to the multi-dimensional response to both quantitative and qualitative functional and non-functional requirements before, during, and after transformation. The design of this type of structure is even more difficult because they are expected to respond to changes in the general requirements which range from technical and operational issues to psychological, functional and formal desires. Transformable architecture, similar to static architecture, requires a carefully planned management and maintenance system in order to guarantee the safety of users and ensure the desired operation of the building, both architecturally and structurally. However, in transformable architecture, due to the nature of transformation which bears repeated opening and closing of the structure, special arrangements should be made to ensure the smooth and reliable movement and articulation of the structural components. One of the crucial problems in the design and planning of transformable architecture is that the architects and structural engineers involved often have little experience of transformable structures. This results in the initial design concept for transformable structures often being developed without much thought given to architectural concepts and engineering details or costs, or the means by which they can be delivered and maintained (http://www.istructe.org [1]). This is a consequence of the limited experience and the natural reluctance of the client to invest in the development of innovative architectural solutions. These problems affirm the importance of the establishment of design and maintenance management strategies for transformable architecture that consequently could reduce fee throughout the whole-lifecycle of buildings. This paper by studying the main issues concerning the design, construction and maintenance of transformable architectural structures will establish a design management model for the design of transformable structures. The design management strategies is aimed to bridge the gap between architects, engineers, contractors and clients in order to create more innovative architectural structures and to reduce the problems that may occur during the life-cycle of this type of architecture.

Keywords: Transformable, Operation, Maintenance, Safety issues, Design Management

1. Introduction

One of the main challenges in the design of transformable architecture is how to devise a transformable structure that most suitably meets the functional and aesthetic requirements of the design brief and at the same time is structurally stable and efficient in open and closed configurations and operates safely and smoothly during transformation. To cope with this challenge and to establish design management strategies, a multi-disciplinary design team is required to analyse the most suitable solution from different points of view ranging from art and architecture to structural, mechanical, material and environmental engineering. The proposed conceptual design should then be developed further in detail by specialist designers and contractors. The next step is to design maintenance management and installation and construction strategies that ensure the efficient workability of the structure throughout its lifecycle and safe and economic installation process. The final step is to devise a means to efficiently demolish the structure and recycle the building's components when it is no longer required (this step must be carefully consider in the design of portable and transportable transformable structures). The following chart (figure 1) provides a brief overview of design constraints and strategies for transformable architecture. This paper by evaluating the main design constraints and strategies will establish a design management model for transformable architectural structure that helps to minise the risk, failure and malfunction of this type of architecture from early stage of design to construction and during usage.

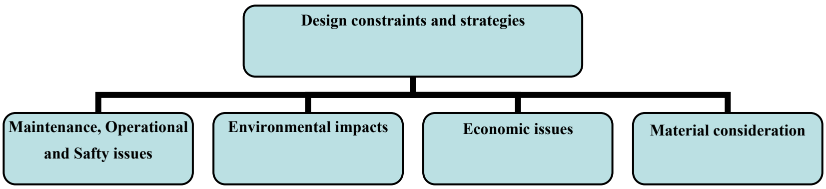

Figure 1 An overview of the main issues affecting the establishment of design and maintenance management strategies for transformable architecture

2. Maintenance, Operational and Safty issues

In transformable architecture, especially buildings with large-scale transformable units, some parts of the structure may wear and need replacement. However both designers and contractors should take steps to minimise the risk of poor performance by ensuring the correct advice is obtained at various stages in the design and construction process. This helps to increase the reliability of the movable components and minimise the costs of both planned and responsive maintenance. Fours steps (explained as follows) is necessary in order to provide a proper maintenance strategies that efficiently reduce the maintenence cost and ensure the safety of users.

Detailed design should carefully consider and estimate operating and maintenance costs. It should also clarify the maintenance and operating requirements and the way this is achieved. The determination of the frequency for maintenance and replacement of the components help the clients in estimating the whole life cycle cost of the project.

The secend step is the provision of comprehensive specifications that are considered both in the design process and in the subsequent operation and performance of the structure. With this, it is then possible to analyse the whole cost of maintenance including the need for regular inspection and identification of the causes of any problems. A mix of performance and design specific specifications shows the inter-relationships amongst different parts of the structure, and can also help the design team to identify the most vulnerable components of the structures.

The third step is the the involvement of manufacturers during the development of the scheme and the detailed design can be helpful to the design team because they are well informed with regards to the possible machinery and components that best meet their design requirements. Consultation with manufacturers can also provide designers with new solutions and possibilities that they have not previously been realised (Lyle [3]). This can consequently can help to reduce the capital cost and maintenance costs of the buildings.

The last stage is the provision of planned and responsive maintenence strategie. Any fault in transformable architecture could cause serious damage that might lead to a catastrophic failure. This issue implies that transformable systems a comprehensive maintenance strategies (including strategies that should have already been devised during the design process to tackle unexpected situations) to guarantee the safety and serviceability of the structures. While it is predictable that most structures that include transformable components will require regular maintenance during their lifetime, the examination of built transformable architecture has proven that operational problems may take place sooner than expected. Transformation and movement of structural components introduces the potential for surface wear that need periodic monitoring, adjustment, replacement and load reversals (Lyle [3]). The consideration of collision avoidance systems such as sonic sensors during the design process can help to minimise the operational failure and ensure the safety of the users. Such systems shut down the system in the event that an obstruction is inadvertently left in the travel path or when a part of operating system fail to do its job properly. It is clear that the difficulties in designing large transformable structures are often not recognized, resulting in poor operation and in some cases failure of key components. One of the main causes of operational failure in transformable architecture, is that both designers and contractors fail to identify or understand the inter-relationship between different phases of design especially between fixed and transformable components. This occurs as different contactors are involved in the construction of different sections of the project with incomplete knowledge about the whole performance specification. Without a good understanding of this inter-relationship, the contractors may not accomplish their task as desired and therefore increase the risk of operational failure.

3. Environmental impacts

One of the crucial challenges in the planning process of transformable architecture is the evaluation and determination of various kinds of environmental and internal forces that may affect the operation of transformable or moveable components. Environmental loads may cause failure in articulated or moveable components at any stage before, during or after the transformation process. Therefore, it is necessary that specialists who are familiar with all aspects of environmental forces are integrated at an early stage in the interdisciplinary design team of architects and engineers. External forces can be categorised into two main groups; predictable forces and unpredictable forces or loads (example: an earthquake). Wind and snow loads are predictable forces- the range of wind velocity and the maximum accumulation of snow in a particular location can usually be determined. However, it is still necessary to take into consideration unpredictable sudden winds that can not be predicted by an ordinary weather forecast, to ensure the safety of the structure in severe circumstances. Special measurement should also be taken into consideration, to ensure the accumulation of snow does not damage transformable architecture. Some possible preventive measures include the integration of automated melting devices in transformable structures or limiting the movement of the structure in snowy conditions (Ishii [2]).

The measurement that should be taken into account against external forces primarily depends on the scale of buildings, transformation mechanism, operating systems, and material together with the frequency of opening and closing and the functional requirements of the design brief. For example, if a structure is required to be in a deployed configuration most of the time, preventive measures to minimise the risk of operational failure is different to that of a structure with other transformation requirements. However, most of the large-scale transformable buildings that are in use today are planned to be closed in severe weather condition (Ishii [2]) as this reduces the whole-life costing of the project and lessens the risk of failure. Earthquake load is also a decisive factor in the design of transformable buildings especially in areas with a high risk of an earthquake occurrence. However, as the exact time of earthquake can not be predicted, it is necessary to install earthquake detector devices, such as a seismometer, in order to control the operation of the structure when an earthquake happens (Ishii [2]). This process should be done automatically by means of locking devices that are directly controlled by a shaking detector device.

Internal loads such as thermal movement of structural components, or forces caused by movement or transformation of a structure, should also be taken into consideration. This type of load can not only affect the operation of the transformable components, but may also cause failure in the static architecture.

4. Material Consideration

Materials play an important role in the effectiveness and the success of transformable architecture. In general, materials used for transformable architecture are categorised into two groups: covering materials and structural and operational materials. Although the selection and the design of structural and operational materials is highly dependant on the structural and mechanical requirements of particular structures, the architectural and aesthetics effects should also be considered fully so that the selected materials do not interfere with the architectural spaces. The examination of major transformable projects reveals that one of the main difficulties for architects in the design of transformable architecture is finding a suitable covering material that not only performs properly as an enclosure for the building, but also resists unexpected environmental changes. It should also meet the architectural requirements of the design brief in terms of light, insulation, etc. The selection of the covering materials is very important for the calculation of the whole-life costing of transformable structures because if they fail during operation, or their mechanical properties change throughout their lifetime, the maintenance and running costs of the building may increase dramatically.

Selection criteria for materials for transformable architecture

Given the variety of materials available today and their multiple functions, it is difficult to categorise them in a concise application-oriented way for different classes of transformable architecture. However, proposing and examining a list of selection criteria is of assistance for designers in making preliminary choices for materials to be used for transformable architecture. The complexity of selecting appropriate materials is added to by the need to narrow down the range of possible materials step-by-step during the design and planning processes in order to reach an optimum solution when making the final decision on the material to be used. The following diagram illustrates the major issues that should be taken into consideration in order to ensure that an appropriate, effective and economical material is selected for a particular transformable structure.

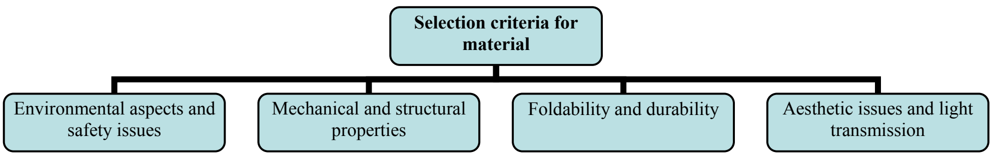

Figure 2 selection criteria for materials for transformable architecture

Environmental impacts and safety issues

The consideration of environmental impacts of a material is of crucial importance in its selection for transformable architecture. The use of composite materials (usually made up of at least two materials out of which one is a binding material and the other is a reinforcement material such as fibre and Kevlar) has reduced the impact on the environment as it has reduced the use of various toxic compounds and increased the use of environment friendly products (Koch [4]). Foldability and movement of materials, in particular in buildings in which the covering material is expected to be frequently folded and deployed, means that the lifespan of the material is usually low and therefore needs to be replaced on a regular basis as part of a maintenance management plan. To tackle this issue, the recyclability of the materials should be considered carefully in order to minimise the negative environmental impact of the material when it is discarded.

As transformable structures face different load and environmental conditions in each state during the transformation process, they are more vulnerable in comparison to static architecture. The application of lightweight and non-combustible materials can decrease the risk of fatalities and injuries of the occupants in cases where the structure was collapsed or failed to operate. It is also a good suggestion to use materials that shrink and do not fall down when they are affected by heat such as ETFE-foils (however, it should be underlined that this material is still under investigation, in use in many buildings though). In order to ensure an appropriate and economical material, it is strongly recommended that designers consult with experienced material companies and engineers during the conceptual planning stages. This helps to validate all possible optimisation factors with regard to material requirements and also helps the designers to check compatibility and consistency of the moving materials with fixed structures. To summarise: well-thought architectural concept should take into account recent technical developments and combine engineering design, material development and experience in manufacture.

Mechanical and structural properties

The deterioration in mechanical quality of materials due to the exposure to sun or other weather conditions is one of the most important issues to be addressed in the early stages of the design process. This may affect transformable architecture in two ways; firstly it may decrease the structural strength and resistance of the material against environmental load. Secondly, as a material deteriorates, its flexibility and adaptability is reduced and it turns into a more brittle material. Consequently, the structure may fail to operate properly, especially when the material is arranged to be folded during transformation. The problem may also damage the other structural components connected to it.

Thermal insulation materials play an important role in transformable structures. In addition to the form of the structure, the acoustic behaviour is greatly dependent upon the mechanical properties of the material. Covering materials that are used for transformable architecture, due to their low mass, have a very limited effect as acoustic insulation (Fernandez [6]). They are also too thin to offer good thermal insulation. Therefore, in order to improve their thermal and acoustic properties when required, additional components can be integrated into the structure. The architectural concept should carefully consider the effect of thermal and acoustic insulation to make sure that they do not interfere with movement or the transformation of the structure.

One important property of a material that stems from its mechanical properties, is the resistance of the material to soiling. This property is one of the decisive selection criteria for architectural materials, especially for architecture in which, due to the size and form of the structure, was be difficult to clean regularly. In material with a high degree of self-cleaning, dirt and dust particles are unable to stick to the surface of the material and are easily removed by a light rain. It not only helps to reduce the running cost of the building but it also prevents detracting from their appearance. The resistance to soiling and the anti-adhesive coefficient of materials, are preliminary selection criteria for transformable materials. However, the choice of anti-adhesive materials does not guarantee the self-cleaning of the architectural surface- welding quality, detailing and the way in which the covering materials are attached to the static structure are also issues that may have an affect on the degree of self-cleaning.

Foldability and durability

Although durability is not only dependent on the mechanical properties of the materials, it plays a principal role in the effectiveness and safety of transformable architecture. The real lifespan of material is not what is stated by the manufacturer, because the material's tolerance to bending and folding, resistance of the material to mechanical wear and tear also may decrease the durability of the material. Understanding this fact can help designers to plan more realistic maintenance management strategies. Consequently high durable material use can minimise the whole life-cycle costing of the architecture as it decreases the costs of maintenance but also costs need to be spent if the structure fails suddenly. Expected durability may also vary on the extremity of environmental conditions and the frequency of the opening and closing of the transformable structure. For those materials that experience folding during operation, high buckling resistance is one of the crucial selection criteria. This property is one of the determining factors in the life span of the materials. The desired foldability and lifespan of materials should be carefully defined during the early stage of the design process. This helps to select the most efficient and economic material from a variety of materials that offer high buckling resistance. For example, if a transformable membrane is expected to be in use for less than 20 years, PVC-coated polyester may be considered as an economic alternative to PTFE fabric or ETFE foil (Koch [5]). However, the economic consideration is not always a determining factor when two materials have similar tolerance to folding- translucency, strength, self-cleaning ability and many other aspects may affect the selection of the folding material. It should be clearly stated that it is not just folding during transformation that needs a high degree of foldability; this characteristic can also help in the handling and assembly of the materials during construction, particularly in large-scale architecture.

Aesthetics issues and light transmission

The light transmission factor which varies from material to material is of great importance in the selection of a material for transformable architecture. It can not only define the amount of light and heat penetrating into spaces, but it also plays an important role in the visual quality of the architecture, especially at night. The selected material may have an identical transmission factor throughout the area or it may be designed and manufactured with different light penetration coefficients, in order to meet particular architectural requirements. The selection of materials plays an important role in the visual perception and the sense of lightness of architectural spaces specialy for large-scale buildings in which huge load-bearing structures are needed to fulfil the structural requirements of buildings. This issue is more important in transformable architecture as material selection is highly in the integration of inside to outside, and they also can visually lessen the weight of structures. The aesthetic characteristics of materials are dependant upon the mechanical properties, colour and patterning, and are greatly affected by transformation patterns and the form of the structure and the way the materials are supported. The appearance of materials should be considered as one of the most important determining factors in the early stage of the material selection process. It should be clearly stated that a transformable structure, for example a retractable roof in its closed configuration, is perceived as a static architecture. Therefore the choice of transformation mechanism and structural components should be considered with regard to the appearance of the covering materials in this state. It is necessary to correlate and check the compatibility of the space occupied by transformable structures at each step of the transformation, to make sure both structural and covering materials do not interfere with the architectural space.

5. Economic issues of transformable architecture: cost and value

Transformable architecture, due to its high capital cost (meaning cost from design to construction) in comparison with conventional architecture, and the associated maintenance cost that is associated with the preservation and repair of transformable components, operating systems and covering materials, are generally categorized as expensive architectural alternatives. This issue, along with design complexity involving many diverse parameters from architecture and art to structural, mechanical and material engineering and a requirement for skilled workers for its manufacture and construction, has resulted in the value of this type of architecture and the opportunities that it can offer to the area of architecture not yet being properly realized. To address the economic case for this type of architecture, two fundamental questions are proposed and answered in this section. What financial problems may affect transformable architecture from the early stage of its design to its construction? How can the high cost of this type of building be justified by the value and opportunities that it offers?

The costs involved in transformable architecture are costs incurred from the early stage of the design process to construction completion, running costs and costs incurred due to any possible alteration or demolition of the buildings. Although the costing method for transformable architecture is similar to that of conventional architecture, relying on historic costing makes it very difficult to communicate the benefit of this type of architecture. If something is new there can be no historic cost data. Costs of transformable architecture incur expenses that may not properly be addressed while the design brief is being developed. These costs include costs of developing design proposals, making prototypes, studies on the feasibility of the proposed transformation mechanism and the future running and maintenance costs. Financial issues may both directly and indirectly affect the architectural value of transformable structures. The idea of transformation is often thought of by clients as a method to develop and extend the function of a building from an indoor space to an outdoor space. Therefore, what is important for them is to primarily finance the project in order that transformable architecture fulfils this goal. The result of this perception of transformable architecture is that innovative proposals that consider functional, aesthetic and artistic features of transformation are not properly realized by clients. Furthermore, designers may not be allowed to develop their more inventive proposals and consequently these designs are never be built. It can be argued that one of the crucial reasons that transformable frame structures have developed rapidly in recent years in comparison with other types of transformable structures is that they are seen as a more reliable alternative for transformable architecture. This is especially true for large-scale buildings as the design and calculation of their movable units and skeletal components has a similarity to those of static structures. The main difference may lie in the design of the operating system and the analysis of stability and effectiveness of the moveable sections during transformation. However, what is missing in many cases of this type of transformable architecture is a lack of quality of the architectural spaces, in particular when the structure is in the closed configuration. For example, when you are inside the Skydome in Toronto, when it is close, the experience is a dull, dark space surrounded by a massive structure. It seems that this building has been designed to only be used when the roof is open! The question is whether the mission of transformation is only to expand the function of a building without considering the architectural parameters of a pleasant, efficient space. In fact the answer is no, but what can architects do to persuade clients that the money they spend on developing an architectural concept, the prototype making and even the research on architectural applications of transformable structures, can add long-lasting value to the final result? In order to do that, architects and designers should develop and expand their structural understanding of transformable systems. It does not mean at all that architects should learn how to calculate and analyse structures. Rather it suggests that they should be able to integrate their creative architectural knowledge with structural understanding in order that they can propose transformable structures that not only meet the architectural requirements of the design brief in a creative, artistic way but also ensure both clients and engineers regarding the workability, safety and stability of the building. The most crucial step that architects need to take in order to convince clients is to increase their awareness of the potential of transformable architecture. When clients know that this type of architecture can be applied to a variety of applications from skylights, sunshade devices and expandable screens to compact portable shelters, responsive, smart architecture, retractable roofs and even whole buildings, they might become more interested in investing in the development of transformable architecture from research and design to manufacture and construction. In general, building codes and standards do not provide provision for retractable roof structures. The designer of such a facility must be prepared to present to the authorities sufficient design data, including appropriate reference standards, to demonstrate that all reasonable precautions are being taken in relation to public safety.

It is also necessary to underline the benefits of transformable structures in terms of energy-saving, compactability, portability, speed of construction for small-scale architectural applications, in order to persuade and convince clients that transformable units can be less costly with consideration to their future running cost and are quicker to erect and construct. However it should be clearly stated that transformable buildings may not be a suitable alternative for all types of architecture and architects must integrate both logic and inspiration in order to choose the most suitable alternative during the design process. Clients, engineers and the project manager are less likely to make a reliable judgment about these issues without leadership from architects.

With an understanding of the potential of transformable structures and with the consideration that type of structure is considered as the best or only alternative that most suitably meets a particular architectural design requirement, the question is what measures need to be taken in order to accelerate development? How can manufacturers and contractors be persuaded that a non-conventional design and construction method can be less costly and more beneficial, or quicker to erect and construct, or more likely to finish on-time? It is quite difficult to answer these questions as each type of transformable structure has it own complexities and concerns. However, what can be suggested is that as the design of this type of architecture requires a multi-dimensional integrated knowledge regarding architecture, structure, material, construction and manufacture, everyone in the design team should have a general understanding of the other disciplines. This is in order that they can most efficiently communicate and develop the design proposals. It is a crucial step toward the development of proposals that most properly consider all aspect of transformable structures from design to manufacture. Such close collaboration may also result in designs that cost less, both in capital cost and future running cost and consequently persuade more clients to invest and more manufacturers to become involved.

6. Proposed design management model for transformable architecture

The following diagram (see Figure 3) proposes the main steps that require to be followed for the design of transformable architecture. This diagram is a generic scheme that is designed on the basis of the following issues: Flexibility of the design team to propose innovative, efficient architectural Solutions Preventive measures in order to minimise the risk of design and operational failure Convincing and informing clients during the design process Cooperation of all parties involved the design, construction, maintenance and use of architecture

Although this model can be followed in many transformable projects, particular attributes or legal frameworks for each specific project, should also be considered.

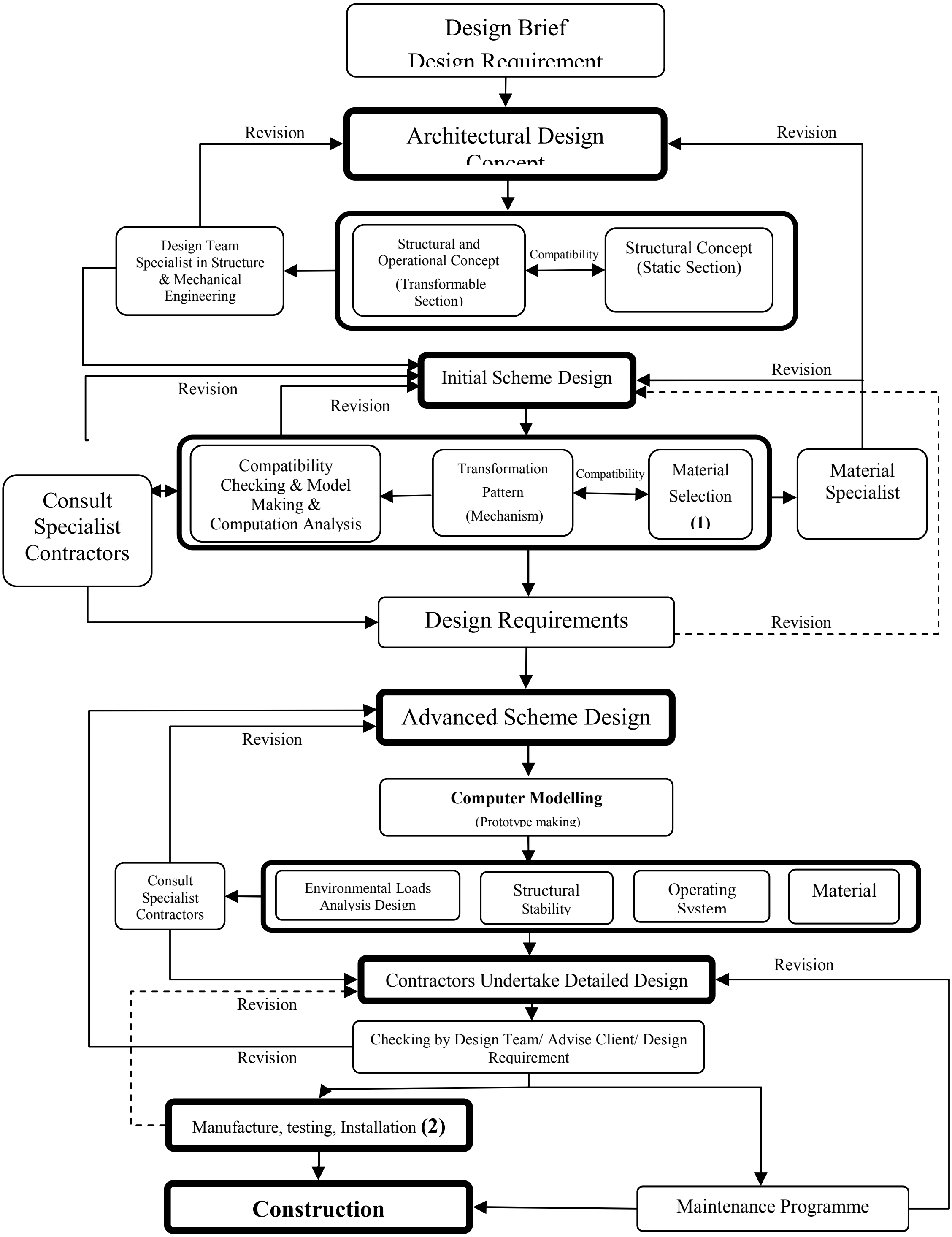
Design Brief
Design Requirement
Architectural Design Concept
Revision
Revision
Design Team Specialist in Structure & Mechanical Engineering
Structural and Operational Concept (Transformable Section)
Compatibility
Structural Concept (Static Section)
Initial Scheme Design
Revision
Revision
Revision
Consult Specialist Contractors
Compatibility Checking & Model Making & Computation Analysis
Transformation Pattern (Mechanism)
Compatibility
Material Selection (1)
Material Specialist
Design Requirements
Revision
Advanced Scheme Design
Revision
Computer Modelling
(Prototype making)
Consult Specialist Contractors
Environmental Loads Analysis Design
Structural Stability
Operating System
Material
Contractors Undertake Detailed Design
Revision
Revision
Checking by Design Team/ Advise Client/ Design Requirement
Revision
Manufacture, testing, Installation (2)
Construction
Maintenance Programme

Figure 3 Proposed general design strategies for transformable architectural structures

7. Explanation of some key issues in the proposed design strategies

As a way of illustrating some differences between the design and construction of conventional (static) structures and transformable ones, some key issues are picked out in Figure as being particularly important in the design and construction of transformable architectural structure. These issues are as follows:

Material selection (1)

As explained earlier, the selection of materials plays an important role in the performance, functionality and aesthetics of transformable architecture. Covering materials in this type of building should not only perform properly as enclosure, but they should also resist repeated movement and environmental changes before, during and after transformation. This issue is especially important because if the selected material fails during operation it may dramatically increase the whole-life costing of the project and endanger the safety of its users. These issues suggest that the selection of proper materials for transformable architecture requires a more complex process in comparison with that of static conventional architecture. As proposed in the chart (see Figure), designers must consider the compatibility and efficiency of materials in different stages of the design process to ensure the safe operation and performance of the structure and consider ease of manufacture, installation and maintenance of the materials. It is also important that the proposed material is checked regularly against the design brief in different stages of the design process to ensure it meets the desired performance requirements and provides an aesthetically pleasing environment for users before, during and after transformation.

Manufacture, testing and installation (2)

Manufacture, testing and installation process is another key issue that should properly be takes into consideration for the design of transformable architecture. This issue is of more importance in transformable structures than static conventional buildings as the detailed design is usually undertaken by different contractors who may propose different arrangements for the manufacture and installation of different phases of the building especially between those that involve static and transformable sections. Testing must be undertaken in different stages of the design process and especially before construction in order to check the compatibility of the operating systems, the performance of the transformable structures themselves, and the functioning of the materials used, to identify any vulnerable aspects of the building. It also can help the design team in the development of the planned and responsive maintenance strategies, which consequently can reduce the running and maintenance cost of the building. Extra attention paid to the manufacture, testing and installation process can also help to improve the selection of the materials in order to achieve the least wear and tear during operation.

Contractors' education and consultation with specialist contractors (3)

As already explained earlier in this paper, the design of transformable architecture differs from the design of (better understood) conventional static structures. It is particularly necessary that all parties involving in the design team properly understand the interrelationship between the different phases of building. A contractor who is responsible for the detailed design of a specific part of a building should regularly be updated regarding the other different parts of the design that are undertaken by other contractors. This can minimise the risk of malfunction of the structure both during construction and in post-construction, during the operation. It is also necessary for designers to consult with specialist contractors in different stages of the design process. This can help them to precisely develop their architectural and structural concepts by understanding the opportunities and problems in advance.

8. Conclusion

This papaer suggests that the design of transformable architecture is only possible by the close collaboration of all members of design team including constructors who are involved in the detailed design of the different sections of a transformable building. All parties involved in the development of this type of architecture should understand the implication and interactions involved in the design, construction and maintenance of transformable structures. In order that the smooth operation and safety of transformable structures is ensured, it is important that the operation of the structure is monitored actively for the duration of its life. This can help to identify any unexpected fault and defection of architecture immediately to prevent other sections of the building being affected. The understanding of the inter-relation between different phases of design, especially between fixed and transformable phases, is very important when the detailed design scheme is developed by contractors. The duty of the design team is to ensure good communication between the different contractors. Various kinds of environmental and internal forces (both predictable and unpredictable) may affect the operation of transformable or moveable components. These should be identified in advance and special consideration should be taken during the design process. It is necessary fort specialists who are familiar with all aspects of environmental forces to be integrated at an early stage into the interdisciplinary design team of architects and engineers. The selection of covering materials is very important in the calculation of the whole-life costing of transformable structures because if they fail during operation, or their mechanical properties change throughout their lifetime, the maintenance and running costs of the building will increase dramatically. Though it adds to the complexity of the design process, it is essential that the design team should carefully narrow down the range of possible materials step-by-step during the design and planning. It helps them to reach an optimum solution when making the final decision on when material should be used. The running costs of transformable structures needs to be addressed whilst the brief and the detailed designed are being developed. It is necessary to define the period of time that a transformable structure is planned to be used for in the early stage of the design process.

References

[1] http://www.istructe.org, 28/10/2008

[2] ISHII, K. (2000) *Structural Design of Retractable Roof Structures*, Southampton, WIT.

[3] LYLE, J. (2006) The design and procurement of movable structures. *The Structural Engineer,* 84**,** 40-45.

[4] KOCH, K. M. (2004) *Membrane Structures,* London, Prestel.

[5] CHANTER, B. & SWALLOW, P. (1996) *Building Maintenance Management,* Oxford, Blackwell Science Ltd.

[6] FERNANDEZ, J. (2005) *Material Architecture,* London, ARCHITECTURAL PRESS.