Sustainable textile architecture: history and prospects

R A Shareef *, H A S Al-Alwan*
*Dept. of Architectural Engineering, College of Engineering, University of Baghdad
Corresponding author’s email: reناسun4@yahoo.co.uk

Abstract. Textiles are now used in various applications in different fields, including the building industry. “Textile Architecture” and “Fabric Structures” are gaining new prominence in the construction world because of their multiple unique characteristics, such as being lightweight, low cost, and durable, as well as offering low energy consumption, flexibility, and resilience. In particular, they are respected for their capability of enclosing large spans with minimal material use and construction time. These characteristics appear to offer the potential to develop a unique textile architecture that can also guarantee environmental sustainability.

Fabric structures have been used throughout history, beginning with the early tents built by humans to provide shelters against harsh weather conditions, where no natural shelters were available, and stretching to the present time, with structures that have been elaborated to meet the needs of more complex applications in different forms, shapes and sizes.

The further development of high-quality materials has triggered a renaissance in textile architecture, yet the current lack of knowledge and limited research on the development of textile architecture and the potentials of such unique structures and techniques in terms of developing sustainable urban contexts, is an ongoing issue. Accordingly, the present paper aims to explore the historical development of textile architecture, and to shed light on the vast range of contemporary modern uses, and architectural applications, as well as discussing the future prospects of this unique sustainable architecture, which may influence the development of new ideas to create aesthetic and cultural contexts within the urban environment. The paper utilises a descriptive research methodology, by tracing the development of such structures to to clarify the recent worldwide progress in the field of architecture in terms of producing outstanding sustainable designs and technical solutions utilising textiles.

Keywords: textile architecture; fabric structures; tents; environmental sustainability

1. Introduction:
The use of "technical textiles" has recently become widespread, though applications of textiles in industries other than clothing have occurred since early history, with fibres, yarns, and fabrics of multiple types being used in applications ranging from engineering to the production of ropes, sail clothes, canopies… etc. [1]. A key application of technical textiles is in architecture, a process thus known as "textile architecture". The use of textiles in architecture, as displayed by the development of "fabric structures", has a long history, dating back to 40,000- 44,000 BCE, ranging from the period of pre-historic age, and continuing into the modern day. Though, this field of application is witnessing noticeable development day by day [2]. Such structures have many modern uses and valuable applications in architecture based on responses to human needs and the demands of various activities. The following sections reveal the historical development of textile architecture, with a special emphasis on modern uses and applications towards achieving remarkable sustainable architecture that can enhance the urban environment.
2. Textile architecture in ancient times:

Fabric structures have been used by humans since ancient times, when simple textiles made of animal skins (leather, fur, wool or hair), tree bark, or palm fronds were used to cover wooden frames made of tree branches or heaped animal bones to provide early shelters or dwellings, where materials that are used to build more permanent shelters were rare, or when there was a need for temporary shelter, as well as providing protection against extreme weather conditions such as sun's heat, wind, rain, sandstorms, and snow [3].

The origins of textile structures can be traced back over 44,000 years, from the ice age in the Siberian Steppes; where remains had been discovered and identified as “simple tent-like shelters” created by Mousterian cultures (Neanderthals who lived in the Middle Palaeolithic period in Europe), and their tents were characterised by low-domed shelters constructed from animals skins tied to timber frames of tree sticks [2], or attached to the accumulated bones of mammoths [4] (Figure 1a). Dillehay also documented conical-shaped timber-framed structures covered with mastodon skins found in Chile that dated back to approximately 13000 BCE [5] (Figure 1b).

Archaeologists have discovered seasonal housing sites in Pincevent in France that offer evidence of tents made of wooden poles supporting animal skin covers dated to 8,000 BCE, which had been assumed to be built by nomadic peoples who changed their settlements seasonally [6] (Figure 1c), while excavations in Russia have produced remains of lightweight housings created from conical structures made of wood, and even other remains of structures erected from animal bones covered with tree bark or animal skins (belonged to the Stone Age) dating back to 4000 BCE [4] (Fig.1d).

![Figure 1. Ancient historic tents](image)

(a) A low domed shelter back to the Mousterian tribes, (44000 BCE) [4].
(b) A conical shelter, Chile (13000 BCE) [4].
(c) A conical tent, France (8000 BCE) [6].
(d) A conical tent, Russia (4000 BCE) [4].

Nomadic cultures around the world have used animal skin as fabric, to cover wooden structures to create shelters (traditional tents), with many different designs, sizes, and shapes emerging over thousands of years, up to date. The most common examples of traditional tents in ancient times would be illustrated below:

2.1 Conical tents:

2.1.1 Keti:

This tent type was widely used by the Lapp tribes, a nomadic people from Siberia. These were covered with reindeer leather, or softened bark [6] (Figure 2a).

2.1.2 Tupiq:

Used by the Inuit tribes of Northern Canada and the Eskimos in Alaska. The design of the tupiq is similar to that of the keti, with a demountable, conical wooden framed structure covered with a caribou or seal skin. However, a tupiq has no upper chimney [6] (Figure 2b).

2.1.3 Tipi, tepee, or teepee:

Used by the Red Indians of North America. Tipi is the most developed among the conical-shaped tents, being characterised by the use of a double-layer of animal skin (bison), which makes the inner space warmer in winter and well ventilated in summer [6], (Figure 2c).
2.2. Mongolian tent (cylindrical type):

2.2.1 Yurt, yurta, kherga, kabitka, or ger:
The Asian-Mongolian tent used by East Asian tribes and residents of the Asian plains from China to Iran. It consists of multiple layers of mat or felt coverings rather than tensioned fabrics; these are then wrapped with ropes around the perimeter [6] [8] (Figure 3).

2.3 Textile fabric tents (velum type):

2.3.1 The Bedouin nomadic black tent:
Such tents, made of goat hair, are still used by the Arab Bedouin tribes. This represents one of the most successful, simplest, and oldest textile fabric structures, and forms the basis of many contemporary tensile fabric structures [3] (Figure 4a).

2.3.2 Tibetan tent:
These are also known “black tents” or “spider tents”, and they are used by the tribes in the Tibetan plateau. The structure is covered with yak leather [9] (Figure 4b).

2.3.3 Tuareg tent:
These were used by the Tuareg nomads (Berber tribes) in the north-western part of the Great African desert. The structure is covered with animal hides or mats [10] (Figure 4c).

Although all these traditional tents rely on materials with relative durability of limited duration, they provide high levels of comfort for their occupants during their lifespans.
2.4 Semi-vault tents:
During the excavations of the ancient Babylon and Sumer civilisations in Iraq, archaeologists found evidence of ancient markets very similar to their “modern” ones in the 1930s in that both had temporary commercial stalls covered with top canopies or awnings made of fabric to protect shoppers from the direct sun [11]. Similarly, a stone relief was found in Nineveh (Mosul), in Iraq, which was identified as showing an Assyrian tent from the Sennacherib camp of the Assyrian Empire (704 - 681 BCE) (Figure 5). The tent structure had central poles with fork branched upper ends forming a semi-vault structure covered with animal skin, felt, or woven fabric, which was attached by ropes and fixed directly to the ground [4].

![Figure 5. Semi-vault tents](image)

3. Textile architecture in the classical and Roman period (100 BCE to 400 CE):
Textile architecture had evolved over time significantly in Europe, leading to the building of lightweight structures characterised by large scale sizes; this development derived from the advantage of sailing experience, which represented the first step into the development of architectural fabric structures [12]. Notable and outstanding examples for such structures of this period include:

3.1 The retractable textile roof of the Colosseum 70 - 80 CE:
Studies on remains such as coins, frescoes, and reliefs has indicated that "textile sunshade roof systems" were applied to theatres, amphitheatres, circuses, and stadiums by the Romans, in Rome in the first century BCE, and these were then spread to other European regions and even north Asia (Turkey). These textile covers were built by the reuse of old naval sails, and this step can thus be considered a significant milestone in the transformation of the technology from maritime into architectural use, in the form of ephemeral lightweight textile shading structures [6].

The Velarium (Velaria or Vela) was one of the earliest main applications of temporary textile roof apparatus, which was built by the Romans to cover the Colosseum amphitheatre to block the sun and protect the spectators during hot summer daylights. This retractable cover was characterised by its foldability, thus allowing it to be retracted and folded to provide an open area up to the sky and allow airflow during sticky summer nights [13] [14] (Figure 6). Nowadays, this tradition is being used in the form of “todlos” and “awnings” in Mediterranean regions and southern Spain, and even in the coverings of contemporary stadiums [2] [15].

3.2 Military Tents:
Military tents were first designed and developed by the Romans in response to army requirements. These tents were made of fabric or animal leather with inclined roofs. These tents were temporary, portable and mobile structures, which could be assembled and dismantled in site. However, this tradition of utilising such portable structures has been inherited in many parts of Europe [6]. Archaeological excavations of Roman remains have allowed the discovery of these tents through drawings, such as those, which were engraved over Trajan’s column, including the “papilio” or butterfly tent [4] (Figure 7).
4. Textile architecture in the Ottoman period (1299 - 1923 CE):
Textile structures during the Ottoman Empire were represented by tented buildings used for military purposes, seasonal trips, and housing important imperial occasions. These tents were often linked to each other, forming complexes of interlaced tents of different purposes, sizes, and forms (conical, marquee, trapezoid, or circular) [6]. The most important tents were the “imperial tents” of the Ottoman Sultans, known as “Otağ” or “Otak”. These tents acted as temporary mobile palaces or mobile pavilions, characterised by decorated gilded ornaments and paintings over the fabric (cloth or leather) and columns, (Figure 8). Such tents, for the Ottomans, were clearly symbols of power, identity, and wealth [16].

5. Textile architecture in the Renaissance period in Europe (1300 to 1600 CE):
The use of tents for military applications begun by the Romans, was continued by the Byzantine armies until the 7th century. During the 12th century, royal tents were first used for public or special occasions in Europe. Royal tents were developed over the years, and by the 16th century, they had become bigger and more ornamented, gaining more architectural significance and becoming symbols of frivolity, fun and entertainment [2].
Royal tents were very popular in the European royal courts during the renaissance and baroque periods, and this played an important role in the development and growth of textile architecture, by erecting temporary textile structures for entertainment purposes that showed and reflected their power, glory, prosperity, and dominance almost anywhere [12].
Outstanding examples of the use of royal tents are found in the royal banqueting and entertainment tents created for the event known as the Field of Cloth of Gold, technically a political meeting between the British king, Henry VIII, and the French king, Francis I, in France in 1522. The resulting complex
consisted of one major tent surrounded by 16 minor ones. The major tent consisted of a wooden circular structure with a central mast that rose up to 40 m high, to support a double skin membrane pitched roof and vertical walls. The external layer was made of a waterproof fabric, while the inner layer was decorated with ornaments that represented the “sky” (Fig.9). The minor tents also had wooden structures, and these rose up around 12 m high [6].

Figure 9. Royal European tent (Henry's tent) for the Field of Cloth of Gold [12].

6. Textile architecture in the 18th and 19th century/ The Industrial Revolution age:
After textile architecture’s development of simple and traditional tents, textile materials played no noticeable role in architecture until the second half of the 19th century. Textile materials were not accepted as a major building material before that period due to their minimal longevity and transient nature [17]. Concurrently, with the development of materials and building technologies during the industrial revolution, the textile industry using mechanical spinning became popular and spread widely, especially in England. This offered people the ability to build large portable and mobile tents that could be installed and dismantled quickly and easily. These tents were adopted for various recreational purposes, such as traveling circuses, at the end of the 19th century [18]. Besides recreational purposes, textiles were used for health purposes, covering social activities, and for acoustic and sound dampening, at the late 19th century and the beginning of the 20th century. Natural fibres such as cotton, linen, silk and wool, were the main raw materials used to produce textile fabrics during that time. Coated textiles were first used in the 18th century, being coated with flax oil; these were then replaced with rubber in the 19th century, which represented the first attempts to produce multi-layered materials with weatherproof properties [12]. Notable textile structures emerging during the industrial revolution included:

6.1 Travelling/ Transportable/ Movable Circus Tents:
Changes in circus tents represented several major development in textile structures during the industrial revolution. In the late 17th century, the first circus tent was erected with a diameter of 15 m. Then, by the end of 18th century, larger circus tents, referred to as “big tops” with diameters of 50 m were produced for multiple-cast performances; these were transported around Europe and USA by railway. This development occurred in parallel with the establishment of Stromeyer's Co., in Germany, which made major contributions to developing textile fabric structures [2].

6.2 Types of Circus Tents:
6.2.1 Framed tent:
These frame structures had an independent frame, made of wood or metal, that was covered with a weatherproof canvas, creating a type of structures suitable for large open flat areas (open gardens). A notable example was used by the “Cirque Palisse”, in 1911, which featured a round wooden structure with a diameter of 36 meters, covered with a fabric [6] (Figure 10a).

6.2.2 Parasol, umbrella, or “chapiteau” tent:
These tensile structures used one or more masts to support the tensioned textile roof and were characterised by resistance to climatic conditions. This type of structure was most suitable for limited
hard areas. Notable examples included the Barnum and Bailey tents of The Greatest Show on Earth carnival of 1898. This complex had 12 huge pavilions formed of water repellent fabric, and the diameter of the main circus tent extended up to 50 metres, creating an inclined roof [6] (Figure 10b).

6.3 Temporary Hospitals:
The use of textile structures as temporary mobile hospitals began in the 18th and 19th centuries; these both housed the war-wounded and were used to isolate people with contagious diseases, being most frequently used by the US army in the late 19th century [20] (Fig.11a). In 1918, this experience was successfully implemented in Europe and the USA, where by erecting temporary open-air hospitals, patients infected with Spanish flu were encouraged to get better faster without infecting others [21] (Figure 11b).

6.4 Other Functions:
Other functions of textile structures developed at the beginning of the industrial revolution, including the use of sunshades or covers for recreational activities such as restaurants and other social activities, providing shelter for users. In the middle of the 19th century, textile structures began to be incorporated into glass facades to provide sunshades for French markets and English greenhouses, and into interior spaces to provide sound insulation, as in the "acoustic membranes" used inside the Crystal Palace at the Haendel Festival in London, in 1859 [13] (Figure 12).

7- Textile Architecture in the 20th Century:
Textile architecture underwent several revolutionary developments during the 20th century, especially after World War II, when the technology of lightweight structures was transferred from various aviation
and military applications into architecture. New textile materials, polymers, fabrics, fibres, and coatings were also developed during the 2nd half of the century; thus, finding new applications in industry and architecture. Since then, textile structures became larger and more complex, with various shapes and sizes used to enclose larger spaces with different functions related to human activities such as events, pavilions, exhibitions, stadia roofs… etc. [12].

7.1 Materials:

The rapid development of tensile structures in the second half of the twentieth century was primarily due to developments in polymeric chemistry, which led to the production of various synthetic materials characterised by lightness, high performance, and efficiency [22]. In 1947, polyester fibres were introduced to the industry, then in the late 1960s, Polyvinyl Chloride (PVC) was adopted as a basic coating material for textile structures. Due to the increasing need to create more permanent membrane structures in the early 1970s, fiberglass coated with Teflon®, or Polytetrafluoroethylene (PTFE), was produced as a more durable alternative solution than PVC- coated polyester. PTFE-coated fiberglass had a life expectancy of at least 20 years compared to PVC-coated polyester’s lifespan of 10 to 15 years. In the 1990s, modern foils and films such as Ethylene Tetrafluoroethylene (ETFE) were first used for various architectural purposes, and ETFE is now used in the form of multi-layer foil cushions, rather than as a single-layer membrane, to enhance solar and thermal insulation [23].

7.2 Structures:

7.2.1 Development of Textile Structures in the 20th Century:

The development of modern textile structures began in the 1950s, with the work of the German architect Frei Otto, and in conjunction with the ongoing development of cable net structures. Later, Horst Berger progressed this work in the 1970s and ‘80s, while the work of Walter Bird on pneumatic structures and Richard Buckminster-Fuller’s work on tensegrity structures contributed to the birth and development of contemporary textile structures [23]. Early designs by Frei Otto expressed modernity, lightness, and aesthetic attractiveness by using organic free shaped tented forms that also offered sustainability and flexibility; further, they offered savings on costs, time of installation, and ease of dismantling. These expressed the potential of textile architecture to exceed the limitations of conventional structures. The work of Horst Berger went a step further, incorporating local culture as well [6].

7.2.2 Types of textile structures:

7.2.2.1 Tensile cable net structures:

These tensile structures consist of a network of interlaced or interconnected cables, with a transparent material cover acting as a secondary element [24] (Figure 13).

7.2.2.2 Tensile/tensioned membrane structures (Fabric membranes):

This type of structure developed from cable net structures, having a tensioned membrane as a structural element to undertake the functions of loadbearing and covering, in addition to the standard supportive elements [24] (Figure 14).

7.2.2.3 Pneumatic structures (Air-structures):

These structures are completely dependent on air, which is used to inflate the flexible membrane and to balance the whole structure, in addition to the anchoring elements [3] (Figure 15).

• Air-supported structures:

These have a single-wall or balloon-like structure filled with air maintained at a pressure slightly above atmospheric pressure using air blowers [26] (Figure 16).

• Air-inflated structures (Inflatable Structures):

These have double-wall (double-layer) structures where the skin is shaped into tubular or cellular forms before being pressurised using air to create structural stiffness; the usable space is thus hollow rather than pressurised [26] (Figure 17).
Figure 13. Tensile cable net structures
a- Raleigh Arena or Dorton Livestock Arena, USA, 1952 [18].
b- German Pavilion, Montreal Expo 6, 1967 (cable net – outer layer covering a PVC-coated polyester fabric- inner layer) [18].
c- Munich Olympic Stadium roof, 1972 (cable net covered with acrylic panels) [18].
d- Millennium Dome, UK, 1999 (PTFE-coated glass fibres, supported by a cable net) [2].

Figure 14. Tensile/tensioned membrane structures
a- Music Pavilion, Kassel, Germany, 1955 (cotton fabric membrane) [10] [12].
b- Dance Pavilion at "Cologne Federal Garden Exhibition", Germany, 1957 (cotton canvas and polyester fabrics) [12].
c- Jeddeh Hajj Terminal, KSA, 1981 (PTFE-coated fiberglass fabric) [23].
d- Denver International Airport roof, USA, 1995 (Teflon-coated glass fibre membrane) [6].

Figure 15. Pneumatic structures
a- Air-supported Structures [25]. b- Inflatable Structures [25].

Figure 16. Air-supported Structures
a- Radome enclosure, USA, 1948 (urethane-coated polyester fabric) [3].
b- Pool Enclosure, USA, 1957 [10].
Since the middle of the 1970s and '80s, textile structures have developed rapidly, and these now include permanent installations that meet both the functional and aesthetic needs of a wide range of different purposes [28]. In the late 1990s, textile structures were also attached to facades to act as envelopes, often to provide natural lighting for interior spaces (Figure 18) [12]. Later, this technique was further developed and used with a range of different projects such as malls, libraries...etc. [28].

### 7.3 Basic shapes and forms:

Three-dimensional tensile structures typically form doubly curved shapes that are either anticlastic (saddle-shaped) or synclastic (dome-shaped) (Figure 19a). They also can be designed to take on various free-form designs, such as hyper, conical, weave, arch form, and cushion/pneumatic variants [29] (Figure 19b).

### 7.4 Form Finding Development:

Many early examples of modern tensile structures were designed based on studying the characteristics of soap bubble surfaces as applied on small physical models, and Lycra textile physical models used to calculate the resulting structure's ability to bear the imposed loads and likely weather conditions (rain, snow, wind, etc.) [22] (Figure 19). These models increased the possibility of finding and developing new forms.

Alongside the use of soap bubble models, Frei Otto was really inspired by nature, and sought to mimic biological structures in terms of both form and function (biomimicry), inspiring forms based on aquatic microbiological organisms (planktons) and studying the principles of natural structures such as
spiderwebs, plants, vertebrates, etc. He also applied these principles to textile architecture; hence, produced more innovative forms supported by cable nets, tensioned membranes, and pneumatic structures [31].

During the 1970s, the form finding process was developed by using numerical methods (also known as digital methods or computational methods) such as the force density method (FDM) and dynamic relaxation (DR). The Munich Olympic Stadium was the first major project designed using this method [18] (Figure 20).

8. Textile Architecture in the 21st Century:
Several technological developments have emerged during the last two decades.

8.1 Recent Contemporary Technological Developments:
According to the influences of the pioneers of lightweight structures in the mid-20th century, many current developments that focused on social needs, cultural contexts and design methods, encouraged architects and designers to develop new forms. The second half of the 20th century and the beginning of the 21st century witnessed enormous incremental use of textile architecture, which necessitated the need to make a fundamental change in conceptual design thinking and in the perception and realisation of construction performance and behaviour in terms of load distribution and transfer [32]. Hence, this era has witnessed a wide range of development at multiple levels, including the widespread use of computers and computational programs (CAD) and developments in the manufacture of contemporary structures, as well as developments in material techniques and technology.

8.1.1 Developments using computers and computational programs:
Alongside the use of computational programs to calculate the forms and patterns of textile structures based on using equilibrium equations to determine the tensional forces and loads and other forces imposed upon the structures, developments in computer technology and computational programs (CAD/CAM) such as Testa Architecture’s Weaver, Tensys’ inTENS, Weaver, Rhinoceros, CATIA, and Maya, have contributed to progress in tensile fabric and pneumatic structures. These programs have extended the possibilities of getting more developing complex forms inspired by nature, minimising implementation time and improving both quality and performance. Such techniques have now been used to produce several famous project designs including the Olympic Watercube in Beijing, China, 2008 (Figure 21a) and the Cutty Sark in London, UK, 2006 (Figure 21b), which were both designed by Nicholas Grimshaw [33].
Theorists and designers such as Lars Spuybroek, with the aid of sophisticated computer programs, have also tried to imitate and simulate physical textile principles and techniques (weaving, knitting, braiding, etc) into architecture; thus, producing complicated mega scale textile-like forms or structures (megatextiles). This concept, known as "textile tectonics", was adopted by the proposed design for the renovation of the Magasins Generaux existing building in Paris, France, 2004 [33] (Figure 20c).

8.1.2 Developments in manufacturing contemporary structures:
Research studies at Stuttgart University have led a team to design innovative lightweight textile structures by using the unique characteristics of composite materials such as fibre reinforced polymers (FRP), including carbon fibre reinforced polymers (CFRP), and glass fibre reinforced polymers (GFRP). The principle underlying these structures is the mimicry of biological fibre systems, through the creation of a series of research pavilions that have focused on the following factors [34] [35]:

- **The potential of modern designs**: Studying the properties and characteristics of living organisms (biological structures), such as the chemical structure of the chitin layer that covers beetles, allowing such concepts to be translated into architecture.
- **Biomimicry**: Studying the properties of natural polymer composites of many organisms, such as spider webs, the silk cocoons of some insect larvae, protective beetle shells, collagen in animals, and cellulose in plants, allowing these principles to be applied to create light, strong, and sturdy structures.
- **Computational simulations**: Using advanced computational modelling programs.
- **Robotic fabrication processes**: Using robots that are connected to computers to fabricate structures by spinning and winding (weaving) carbon and glass fibres together to shape final products as single cells or as whole objects, unlike traditional and technical weaving techniques; thus, creating and producing distinctive free-form structures.

Prominent projects designed using these principles are shown in Figure 22.
Developments in manufacturing contemporary structures (University of Stuttgart projects that mimic nature)
a- ICD/ITKE Research Pavilion 2012, (black carbon fibres are woven with transparent glass fibres so the structure mimics a spider's legs and webs) [34].
b- ICD/ITKE Research Pavilion 2015, (an outer layer of pneumatic ETFE film, supported by an inner layer of carbon fibres to mimic the biological systems of water spiders) [34].
c- ICD/ITKE Research Pavilion 2017, (featuring a long cantilever in multi-layer of carbon and glass fibres reinforcing polymers that mimic a larva’s silk cocoon) [35].

8.1.3 Developments in material technology:
Alongside the use of polymeric materials, represented by textile membranes and coatings, as an economic and rapid architectural solution, new materials such as smart textiles began to emerge at the beginning of the first decade of the 21st century, offering new reactive and adaptive construction materials [10], chromic materials, phase change materials (PCM), conductive optical fibres, and shape memory materials (SMM), which all contribute to the current development of textile architecture by allowing the creation of smarter, more flexible and durable building structures, with aesthetic architectural forms that are suitable for large open spaces yet allow savings in costs and energy [12]. Prominent examples of modern innovations using smart textile materials are shown in Figure 23.

Figure 23. Developments of material technology
a- Allianz Arena, Germany, 2005, (LED lights are integrated into ETFE foil cushions, controlled by a digital system that adapts and changes the lights colour according to activities held inside the stadium) [10].
b- Future Smart Tent proposal, Canada, 2013, (An adaptive eco refugee shelters, each tent has a tank to collect rain water, even solar cells are embodied into the tent's fabric to generate electricity and heat) [36].
c- King Fahad National Library, Saudi Arabia, 2014, (The façade's membrane controls sun's incidence and solar transmittance into the building and works as a sunshade system) [10].
8.1.4 Recent innovative techniques in membrane technology:

Recent research and developments have led to many innovations in textile architecture:

8.1.4.1 Integrated flexible photovoltaics:
Flexible photovoltaics can now be integrated into PTFE, ETFE film/foil cushions, and HDPE membranes to provide shade and electricity [37] (Figure 24a).

8.1.4.2 Translucent thermal insulation:
This allows integration and filling with translucent silica-aerogel among multi-layered membranes [39] (Figure 24b).

8.1.4.3 Membranes as a second façade:
Integrating membranes into façades as second skin provides light and natural ventilation and reduces energy consumption [37] (Figure 24c).

8.1.4.4 Standardised/modular membrane elements:
Standardised membrane elements with different sizes and areas can be used to replace glass to reduce costs [39] (Figure 24d).

8.1.4.5 Functional coatings:
Functional coatings or so called "selective coatings" such as low-E coatings can be applied to membranes, to transmit light while absorbing UV and IR and reducing CO₂ emissions to less than 40% [37][39] (Figure 24e). Even Nano coatings can be used as topcoats, which are applied to the outer layers of the membrane to keep the surface clean, with a self-cleaning property, such as titanium dioxide (TiO₂) coatings and photocatalytic materials [40] [41] (Figure 23f).

8.1.4.6 Adaptation to surrounding environment and urban context:
Kinetic textile shading devices (roofs or facades) can be used as a tool to adapt to environmental changes, changing form in response to the climatic changes. Other adaptations to urban context include amendments to shape, scale, materials, and patterns that reflect the surrounding context [41] (Figure 24g).

8.1.4.7 Light and solar control techniques:
These systems include digital techniques and changes in air-pressure in pneumatic membranes, printed pattern techniques, and adding colour pigments to membranes [42] (Figure 24h).

8.1.4.8 Smart wrap:
This technique offers a revolutionary development in textile structure industry based on using a single-layered film or a two layered coating system made of PET printed with integrated smart organic LEDs and organic PV systems with phase-change properties as a building envelope, providing transparency, flexibility, thermal insulation, and heat storage [43] (Figure 24i).

8.1.4.9 High clarity ECTFE film/foil:
ECTFE (Ethylene Chloro TriFluoroEthylene), is a thermoplastic fluoropolymer, also known as "Halar® High Clarity ECTFE films ". It is relatively a new product in the architectural industry and a highly transparent film used for building textile structures. It has similar properties to ETFE with extra clarity, solar transmittance (transparency), thickness and printability [40] (Figure 24j).
Figure 24. Recent Innovative techniques in membrane technology
a- Pure Tension Pavilion, Italy, 2013, (PV integrated into HDPE membrane) [38].
b- Solar Decathlon, UAS, 2007, (ETFE panels filled with translucent aerogel) [39].
c- Centre for Gerontology, Germany, 2004, (ETFE as a second envelope).
d- Bergwacht Bayern, Germany, 2008 [39].
e- Dolce Vita Tejo mall, Portugal, 2009, (integrating low-E-coating into ETFE cushions) [37][39].
f- Chapel garden, permanent membrane structure, with TiO$_2$ and photocatalytic, self-cleaning membrane skin, Hyatt Regency Hotel, Osaka, Japan (2001) [41].
g- Kinetic PTFE textile shading umbrellas at Mesjid Nabawi, KSA, 1992, 2012 [42].
h- Cyclebowl, Germany, 2000, adaptive control (opening-closing) of internal pressurised ETFE cushions [43].
i- Temporary structure made of PET-film, Cooper Hewitt Museum, USA [41].
j- Halar® High Clarity ECTFE film with outstanding transparency and printability [44].

9. Conclusions:

- Textile architecture is often considered a new trend, being used currently to construct multiple efficient and aesthetic forms and structures. However, it has been used since ancient times, stretching up today. Nevertheless, new technological developments have been introduced and integrated into modern textile architecture that have led to an increase in its usefulness and acceptability due to the ability to build more sustainable textile structures with unique characteristics such as lightness, rapid installation and dismantling, and economical issues in terms of savings in costs, time, energy and materials, as well as facilitating the use of eco-friendly materials with less impact on the environment, compared to traditional materials.
- In ancient periods, tents came in many different forms (dome, conical, cylindrical and semi-vault), though these were generally characterised by simple wooden or animal-bone structures covered with tree bark or animal skins to create temporary, portable shelters that provided protection against harsh environmental conditions such as rain, snow, wind, and sunlight.
- Textile structure techniques during the classical periods were first developed to allow bigger, large scale and more complicated temporary structures, ranging from retractable velaria that covered amphitheatres to military tents, characterised by their sloped roofs.
- Ottoman tents were used for both military and civic purposes. The imperial tents were splendid and luxurious, being full of gilded ornaments to represent the power, prosperity, and wealth of the Ottoman Empire.
- In parallel with the textile technology of the Ottoman Empire, Europeans during the Renaissance developed Royal tents, which were relatively similar to the Imperial tents of the Ottoman Sultans in terms of their ornamental and decorative appearance and intimations of luxury and prosperity, as well as their waterproof characteristics.
• In the Industrial revolution, textile structures became more complex, being wider, stronger, and built with steel frames covered with waterproof mechanical woven linen or hemp canvas. Tents were created for specific purposes, such as entertainment (circus activities), mobile hospitals, and insulation functions. Circus tents can be considered as developed forms of King Henry's VIII tent from The Field of Cloth of Gold, which offered a prototype for the mobile circus tents of the 19th century, and thus for many of today's entertainment buildings.

• Textile architecture in the 20th century witnessed a series of revolutionary technological developments, particularly with regard to materials, including new synthetic fibres, polymeric membranes and coatings; structural, constructional, and form technologies also developed to produce larger, more complex structures (small, medium and large spans) in both tensioned and pneumatic forms. These temporary and permanent textile structures had forms designed in free organic shapes imitating nature and native cultural contexts. Form finding techniques developed by using soap film and Lycra physical models in the 1950s gave way to digital and computational methods using electronic computers, with functional aspects and new functions emerging to satisfy the needs of new activities, such as exhibitions, pavilions, events, covering sport stadiums, and covering building facades to provide shading with an acceptable appearance.

• Alongside the developments in commonly used membranes (PVC, PTFE and ETFE) in the 20th century, textile architecture in the 21st century has witnessed further developments in architectural textile membrane technologies, and new technological developments that offer innovative solutions to modern issues, including integrating and merging new material and industrial techniques to create interactive, responsive, digitally controlled smart textile architecture that meets human needs and saves energy. This process has benefited from recent computer technology advances in terms of both computational design and modelling and robotic fabrication, which offers outstanding aesthetic results.

• As a result of the enormous technological developments that textile architecture has undergone over time, the desire to use and build textile structures that respond to environmental, economic and social needs is currently increasing.

• Such techniques are both suitable and appropriate for hot humid and hot arid regions, particularly with regard to stabilising whole structures and the use of materials such as PVC/polyester, PTFE/glass, PTFE/silicone, ePTFE (Tenara®), HDPE, PVDF and ETFE. The latter is the best among all, which can resist both heat and intense UV light, as well as being lightweight, (90-95) % translucent, (100) % recyclable, relatively fire resistant, and relatively cheap as compared to glass panels. ETFE can also be used as a single layered-membrane or as a multiple-layered membrane to provide light or enhance shading and heat insulation.

• Due to the current severe global situation with regard to the crises, wars, natural disasters such as the Covid-19 pandemic, floods, and explosions that have caused an excess of immigrants and war refugees, architects, designers, and urban designers must seek to benefit from the wide range of textile architecture qualities and potentials. This could help with the development of urban sites, whether by building structures that cover cities' urban spaces or by creating lightweight, economic, and emergent structural solutions to rapidly house refugees and homeless citizens in the damaged countries caused by military operations (wars), poverty, explosions or floods. These techniques can also be used for building temporary emergency hospitals, or to provide temporary dwellings for immigrants.
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