

Materials for Membrane Structures

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The most prominent material for stressed membrane structures is obviously the fabric. It is prominently present, attracts much attention and looks very simple. To obtain this pleasant charisma there has been done a lot of research. The material is analysed and specific properties are defined and adapted. Properties like transparency, durability, fire retardance but also elasticity, strength.

In this paper the fabric is discussed to get a better understanding of those properties. The composition of the fabric is explained, followed by a discussion of the most common fabrics available today. Finally the structural behaviour of the fabric is discussed.

Threads

A thread is built up out of fibres. There are natural fibres and chemical fibres. Natural fibres have a restricted length and are bound up in strands. These are the so-called spin fibres. Chemical fibres theoretically have an endless length and are called filaments. The cross-section of natural fibres is smaller than 0.1mm, where chemical fibres can have larger cross-sections. The shape of the cross-section is round for natural fibres but can have any shape in chemical fibres. For membrane structures it is best to have a yarn with a circular cross-section.

The mechanical properties of materials in the building industry are normally specified in N/mm². In technical textiles this is not common because it is not easy to determine the cross-section of a very small fibre. Therefore it is usual to determine the weight of a fibre with a certain length. When the specific mass is known from the fibre, it is possible to determine an average cross-section of the material. This mass-per-length unit is indicated with Titer with the symbol Tex: 1 Tex weight in grams per 1 000m length. In synthetic fibres it is common to use decitex: 1 dtex = weight in grams per 10 000m length [7].

A Polyester fibre for example with a Titer of 8.35 dtex has a weight of 8.35 grams at a length of 10000 m. When the product is that small, it is very difficult to use it in industrial processes. Therefore it is spun into threads. One thread possibly consists out of hundreds of fibres. When a thread only has one fibre, it is called monofil.

Spin fibres need to be stabilised by twisting around the centre of the thread. Filaments do not need it, but it facilitates the handling. The twisting influences the stress-strain behaviour of the threads. The more the thread is twisted the more the elasticity decreases compared to the elasticity of the fibre. With the adjustment of the twisting the mechanical properties of the thread can be determined precisely.

The characterisation of a filament thread is according to the System Tex, where the number of fibres and twists are added. A thread for example which is called 2200 dtex f 200 z 60 has a total Titer of 2200 dtex, made out of 200 fibres, the thread is twisted 60 times per meter in z direction [7].

There are several fibres that can be applied in membrane structures. For each project it is necessary to consider which type of fabric can be used. Several fibres do have the potential to be applied, however the high costs of it prevent a wide utilisation.

Cotton fibre

This type of fibre is the only organic fibre, which is being used in membrane structures. Frei Otto used it for his early garden show structures and nowadays it still is applied in some rental tents. As of its organic properties the material is subject to fungi and moisture. When used permanently it has an expected lifetime of about 4 years.

Polyamide 6.6 (Nylon)

The nylon fibre has a bad resistance against UV light, swells in length direction when it gets wet and is herewith of little importance for textile architecture. It is frequently applied in the sailing industry because of the little weight and high strength.

Polyester

Polyester fibre together with fibreglass is the most common fibre in textile architecture and regarded as a standard product. The fibre has a good tensile strength and elasticity. Because of its considerable elongation before yield, the material is "forgiving". It enables to make small corrections during installation. The mechanical properties of the material decrease by sunlight and there is ageing.

Material	Density (g/cm ³)	Tensile strength (N/mm ²)	Tensile strain (%)	Elasticity (N/mM2)	Remarks
Cotton	1.5-1.54	350-700	6-15	4500 - 9000	Only for temporary use of interest
Polyamid 6.6 (Nylon)	1.14	Until 1 000	15-20	5000 - 6000	- When exposed to light only average resistance to ageing - Swelling when exposed to moisture - Only of little importance in textile architecture
Polyester fibre (Trevira, Terylene, Dacron, Diolen)	1.38-1.41	1 000-1 300	10-18	10000 – 15000	- Widely spread, together with fibreglass a standard product in textile architecture
Fibreglass	2.55	Until 3500	2.0-3.5	70000 - 90000	- When exposed to moisture, reduction of breaking strength - Brittle fibres, therefore is spun into filaments of 3 µm diameter - Together with Polyester a standard product in textile architecture
Aramid fibre (Kevlar, Arenka Twaron)	1.45	Until 2700	2-4	130000 - 150000	- Special fibre for high-tech products
Polytetrafluor-ethylen (Teflon, Hostaflon Polyflon, Toyoflon etc.)	2.1-2.3	160-380	13-32	700 - 4000	- High moisture resistance - Remarkable anti adhesive - In air non-combustible - Chemical inert
Carbon fibres (Celion, Carbolon, Sigrafil, Thornel)	1.7-2.0	2000-3000	< 1	200000 - 500000	- Special fibres for high-tech products - Very low expansion coefficient - Non-combustible

Table 1: Material properties of the base material of fabrics [7]

Fibreglass

The material where fibreglass is made of is of course glass, where threads are spun from, which have a certain bending capacity. The fibreglass has a high tensile strength, but remains brittle and has low elastic strain. Because of the brittleness the material needs to be handled carefully and needs very accurate manufacturing. Ageing exerts little influence on the material what has a tremendous impact on the expected lifetime of the structure. But the tensile strength of the material decreases when it is subjected to moisture.

Aramid fibre

This is a relative new type of fibre, discovered simultaneously by Akzo (Twaron fibre) and DuPont (Kevlar fibre). The material has a high tensile strength and is chemically resistant. A drawback is the low elastic strain and the bad resistance against high temperature and UV-light

Composition of the base material

Fabric that is used normally for membrane structures is built up out of a woven structural base material, which has a covering on both sides to protect it from water and pollutants, the so-called coating. There are several ways to establish a coherent woven cloth. The basic method of weaving is called basket bond, where the weft threads pass the warp threads alternating above and underneath. There are a lot of varieties possible, like passing three warp threads underneath and one above.



Fig. 1 Basket bond (left) and Panama bond

Doing this, all kinds of patterns occur like is done in the carpet industry. But for structural use this it is not very sufficient and therefore only the basket bond and

panama bond is used for membrane structures. Panama bond indicates that the weave operation is done with more than one thread at a time. 12*12 panama means that one cm of fabric contains 12 warp and 12 weft threads. At the other hand it is also usual to say 2-2 panama or 3-3 panama which means that the weaving operation is done with two, respectively 3 threads at a time. Panama bond has a better mechanical behaviour than basket weave because of the multiple yarns that are used.

Coatings

In the table above the fibres are described from which the fabric is woven. To create durable and water tight cloths most of the fibres need a coating on both sides. There are several coatings available. The most common ones are PVC coatings, Teflon coatings and silicone coatings. Sometimes not a coating is applied, but a foil is laminated upon the fabric.

The coating often is used to weld the different parts of the membrane together. The adhesion of the coating to the fabric is an indication for the strength of seams. The adhesion of a lamination to the fabric is much lower and therefore requires other connection methods for the seams.

PVC coating on Polyester cloth

This type of coating is used mostly on Polyester fabric. It is either coated or laminated upon the cloth. Dozens of different manufacturers provide such a material, which range from laminated fabrics for party rental tents to heavy coated fabrics for permanent (15-20 year replacement cycle) architectural installations. The fabric comes in numerous colours, has three different top coatings (PVDF, PVF, Acrylic) and is considered a fire-resistive material (see figure 2a).



Fig. 2a PVC coated Polyester structure in the Netherlands After local fire a hole occurs in the membrane, but the fabric itself is not destroyed.

PVC coating on Aramid weave

Another interesting lightweight building material is Aramid fibre used for air tubes. These high-pressure air tubes can take on the support function of a beam, an arch or a grid becoming a type of frame structure. The Aramid fibres are braided into curved forms and bonded to an inner urethane membrane to create seamless inflatable arches of approximate 30 psi. The Aramid fabric is enclosed with a PVC cover to protect the fibres from UV-degradation [1].

PTFE coating on fibreglass weave

Teflon coated fibreglass fabric is the most permanent of the coated architectural fabrics. First employed for a roof in 1973 for the La Verne College Student Centre in California (figure 2b) it has a lifetime of over 30 years. It can be used only for permanent applications and is not relocatable. The fabric is considered non-combustible and as such meets the most stringent building codes worldwide. Off the role it has an oatmeal appearance, which bleaches out to white in the sun after a couple of months. With translucency's up to 25 % it has been used in such projects as the Georgia dome, Denver Airport and currently used on the Millennium Dome.

Silicone coatings on fibreglass weave

Silicone coated fibreglass, which dates from 1981, has been used for Callaway Gardens in Georgia and the tensegrity domes for the Seoul Olympics. Silicone rubber is more flexible than Teflon, and fibreglass coated with it is less likely to be damaged during shipment and erection than fibreglass coated with Teflon. The greatest advantage, however, is that the fabric can be made very translucent, which is claimed to be as much as 25% translucency for the architectural membrane and 90 %

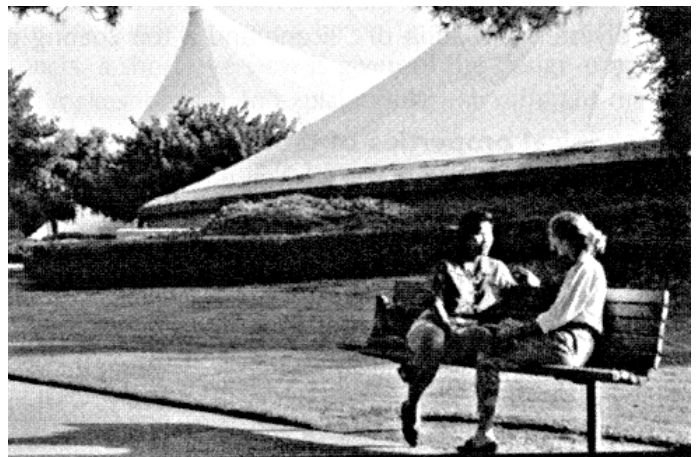


Fig. 2b Oldest commercial PTFE/Fibreglass roof – The LA Verne College Student Centre

	Polyester fabric			Fibreglass fabric	
Coating	PVC	PVC	PVC	PTFE	Si
Top coating	Acrylic	PVF-lamination	PVDF-merging		
Expected lifetime	8-10 years	12-15 years	12-15 years	>30 years	>30
Ageing Resistance	Average	Good	Good	Very good	Very good
Self-cleaning	Average	Good	Good	Very good	Average
Transparency	Good	Good	Good	Good	Very good
Fire-retardant	Good	Average	Good	Very good	Very good
Foldable	Very good	Average	Good	Bad	Average

Table 2 Properties of fabrics [4]

translucency for the thin liner material. With multiple layers of translucent membrane and glass fibre there can be both daylight illumination and very high heat retention. Silicone (Si) is one of the most abundant of the earth's elements, and forms the basis both of the fibreglass threads of the fabric and the silicone rubber of the coating. This similarity in chemical structure allows the design of highly translucent fabrics, while the water protection provided by the silicone coating assures long life span for the fibreglass. With regard to cost and handling, silicone coated fibreglass can be positioned somewhere between Teflon coated fibreglass and PVC coated Polyester.

Recent advantages have partly or wholly resolved early concerns about building with silicone coated fibreglass. Normally the seams are glued, which needs to be done under controlled circumstances. It is said that seams can now be chemically bonded (heat accelerated) to be stronger than the material itself, as with Teflon-coated fibreglass. Some engineers still question whether this process can be adequately applied with patch kits, used on site. The self-cleaning properties have been improved and are said to be equal to Teflon's, yet a once-a-year cleaning is recommended.

Silicone coating on Polyester weave

An ideal fabric would combine the low cost, easy handling and excellent structural behaviour of PVC-coated Polyester with the translucency and long life of Silicone-coated fibreglass, and the high reflectivity and resistance to dirt of Teflon. Is that maybe a membrane with a fabric of Polyester, a coating of Silicone and a top coating of ETFE?

Mechanical properties of fabrics [8]

The fabric behaves in a special way due to the weaving process. Conventional building materials are characterised by their linear elastic and isotropic behaviour. Only when the elastic limit is reached and yield area starts, different rules need to be applied. Materials used in textile architecture have a completely different behaviour and act as following:

- Non-linear, that means that the stress-strain behaviour of the material can not be modelled with a linearization of the curve
- Anisotropy, that means that the material itself has two dominant head directions, which makes all the important mechanical properties direction-dependent.
- Non-elastic, that means that the behaviour of the material is dependent on the added loading.

Non-linearity

At first the non-linearity will be explained. A fabric sample is tested in an uni-axial testing machine. In figure 3 a typical result is displayed from such a test. The stress and strain are displayed.

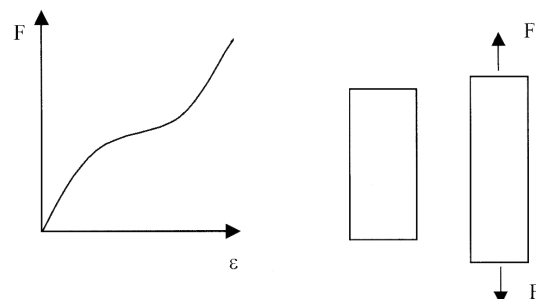


Fig. 3 Typical stress-strain curve uni-axial loaded [8]

It is clear that there is no linear relation between the stress and strain.

Only with a lot of creativity it is possible to draw a straight line along the curve.

Next is the anisotropy to be explained. Therefore several strips are cut out of the fabric, but a different orientation of the fibres is regarded (see figure 4).

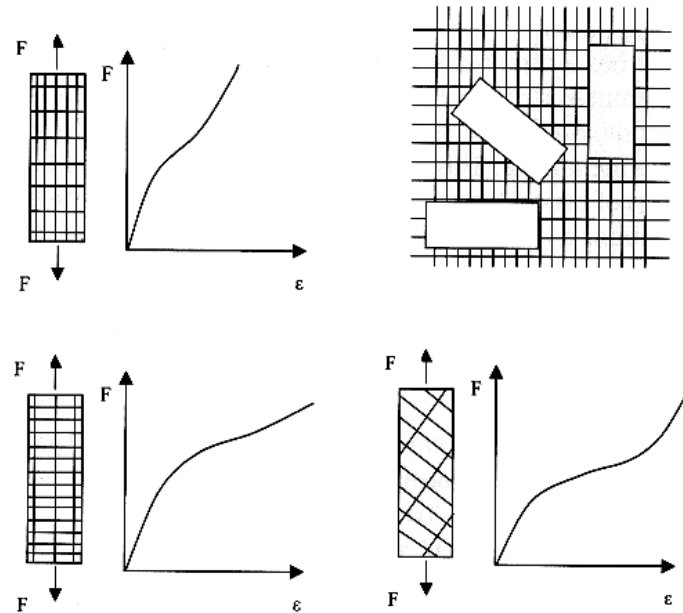


Fig. 4 Anisotropy shown in different fibre orientations [8]

It is obvious that in the different fibre directions there is a distinctive behaviour. This behaviour is caused by the presence of the woven base material in the fabric. During the weaving process, the warp threads are tensioned in the weaving machine and therefore initially straight. The weft threads sneak around them in alternate patterns, as a result of a weaving process in which alternate warp threads are pulled upwards or downwards and a weft thread is shuttled in between them. In the resulting long rolls of fabric, the weft threads running side to side, are kinked around the straight warp threads, which run the full length. In most coating processes this configuration is maintained. One fabricator of Polyester fabric, Ferrari, stretches the weft threads before coating.

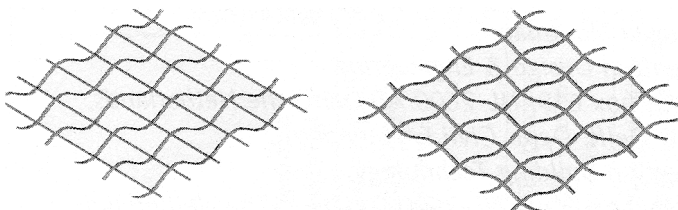


Fig. 5 Left: warp and weft configuration before stressing; right: warp and weft configuration after stressing

The effect of this configuration on the mechanical properties is that the strain is not the same in warp and weft direction. When the warp direction is tensioned, there will be little deformation because the fibres are straight already. When the weft fibres are tensioned, they are kinky, but become straight and therefore have a large deformation compared to the warp direction. In figure 5 the configuration is shown before tensioning and after tensioning.

The last aspect, the non-elasticity is explained by means of the same test examples but then carried out more than once on the same sample (see figure 6).

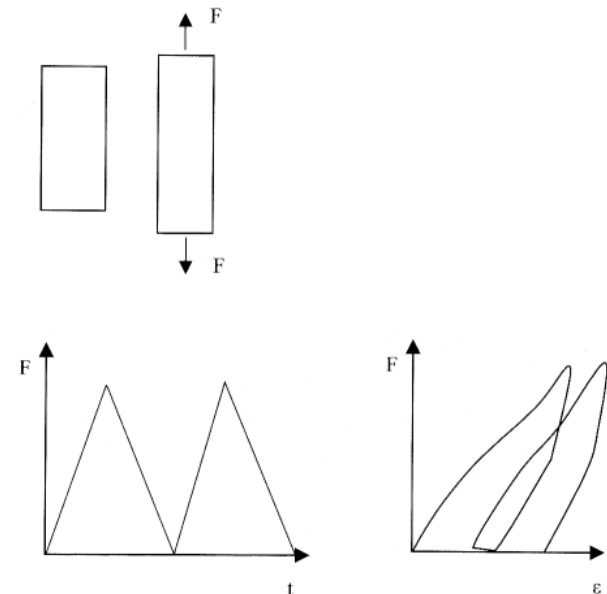


Fig. 6 Non-elastic behaviour of woven material [8]

It can be seen that the loading curve is different from the unloading curve. When the second loading cycle starts, it differs from the first one, as well as the second unloading curve differs from the first one. When the loading cycles are repeated, each loading and unloading cycle is different, although the differences are getting smaller. The difference remains between loading and unloading, which results in a permanent elongation of the fabric. The size of the elongation depends on the previous applied loads. All these aspects act simultaneously. Therefore it is very difficult to describe the mechanical behaviour of fabric with one model. To get a better understanding of those aspects, a short overview is given of the design process. This makes it easier to explain when the different material aspects need to be regarded.

Design process

The design of a membrane structure starts with the formfinding. Since there is a double opposite curvature, there need to be found equilibrium between the

pretension in the membrane and the boundary conditions. This is normally done by means of computer software. Modelling the membrane as a two-way net is a very representative basis for computer analysis. One direction of the mesh can be seen as the warp threads, the other direction of the mesh can be seen as the weft threads. When the boundary conditions are set, a first shape is obtained. This can serve as an image to explain the customer what the shape looks like and if it fulfils the needs. When is decided to go on with the structure, it is necessary to think about the patterning layout. The membrane is built up out of small strips because the fabric comes with rolls of a certain width. The strips are welded together and form the membrane. Because of the anisotropy of the material, it is necessary to orient the warp and weft threads in the head directions of the curvature. The load bearing behaviour is influenced considerably when the head direction of the fabric does not correspond with the head direction of the curvature (see figure 7). There is much more deflection possible as the mesh does not have shear stiffness. So the stiffness of the shape is depending on the adhesion from the coating to the fabric.

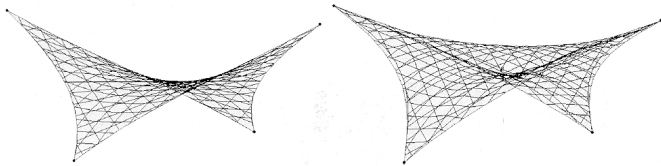


Fig. 7 Two ways of mesh orientation: These result in the same shape but with different load bearing behaviour (1 kN/m² upward load)

When the main direction of the anisotropy is known, the points of departure for the stiffness of the structure can be determined. With these values a statical analysis is made, which results in forces in the primary structure and the membrane. The results of the statical analysis on stresses and deformation are used to check the loading limits and failure modes. For membranes the following failure modes are critical:

- Failure of the bi-axial loaded membrane within the assumed lifetime of the structure
- Failure of a seam or connection of membrane to primary structure
- Tear failure during installation or because of vandalism.

The first failure mode is depending on the safety factors used upon the ultimate strength of the material. The difficulty of the non-elastic material property is dealt with in a very simple way. Just a small amount of the strip tensile capacity is used. Depending on the used fabric, there is the risk of brittle failure (fibreglass) or large plastic deformation (Polyester). So for permanent loading sometime a ratio f 1/8 is used, for windloads 1/4 is used and for snowload 1/5 is used because it can last for several weeks and therefore is a semi-permanent loading. According to the DIN, the design load cannot be larger than $0.85/3.1$ *strip tensile strength. Another approach is to stay under the tear strength of the material to prevent tear failure. This results in a ratio of 1 /5-1 /6.

Fabric/ Coating	Weight [g/m ²]	Fire retardant	Tensile strength Warp/weft [N/50mm]	Tensile strain Warp/weft [%]	Tear strength [N]	Bending capacity	Seam strength [N/50mm]
Polyester/PVC Type 1	800	B1	3000/3000	15/20	350	Very good	2400 (30mm, 70'C) 2850 (60mm, 70 'C) 3350 (60mm, 70 'C) 4600 (60mm, 70 'C) 4600 (60mm, 70 'C)
Type 2	900		4400/3950	15/20	580		
Type 3	1050		5750/5100	15/25	950		
Type 4	1300		7450/6400	15/30	1400		
Type 5	1450		9800/8300	20/30	1800		
Fibreglass/PTFE	800 1270	A2 A2	3500/3000 6600/6000	7/10 7/10	300 570	Sufficient	6000 (60mm, 70 'C)
Fibreglass/Si	800 1270	A2 A2	3500/3000 6600/6000	7/10 7/10	300 570	Good	
Aramid/PVC	900 2020	B1 B1	7000/9000 24500/24500	5/6 5/6	700 4450	Good	4800 (30mm, 70 'C)
PTFE/-	520	Non com- bustible	2000/2000	40/30	500	Very good	
Cotton- Polyester/ -	350 520	B2 B2	1700/1000 2500/2000	35/18 38/20	60 80	Very good	

Table 3 Mechanical properties of common fabrics [7]

So there are several ways the admissible tensile load is determined.

The second failure mode, failure of a seam, should be avoided by testing which seam width is needed at which temperature. When the temperature rises, the seams get weaker. Above 70° the strength of the seam gets considerably lower.

Tear failure (the third mode) often occurs during installation. It starts at an open edge or at a hole in the fabric. It is critical, therefore, that the fabric panels are contained all around the edges, with a continuity that is meticulously maintained. Most commonly, edge ropes in continuous sleeves, which are connected cables or other structural members, achieve this. Another cause for tear failure is the acting of tangential forces in the membrane. When no proper take-up of these forces is provided, the fabric can tear under heavy loading. When the quality of the membrane is determined, the cutting patterns can be made from the final shape. The shape has a certain pretension, and the patterns need to be compensated for that. The needed compensation is depending on the strain of the fabric under the prestress in the membrane. This strain needs to be investigated by means of biaxial tests on the fabric under similar prestress conditions as present in the membrane.

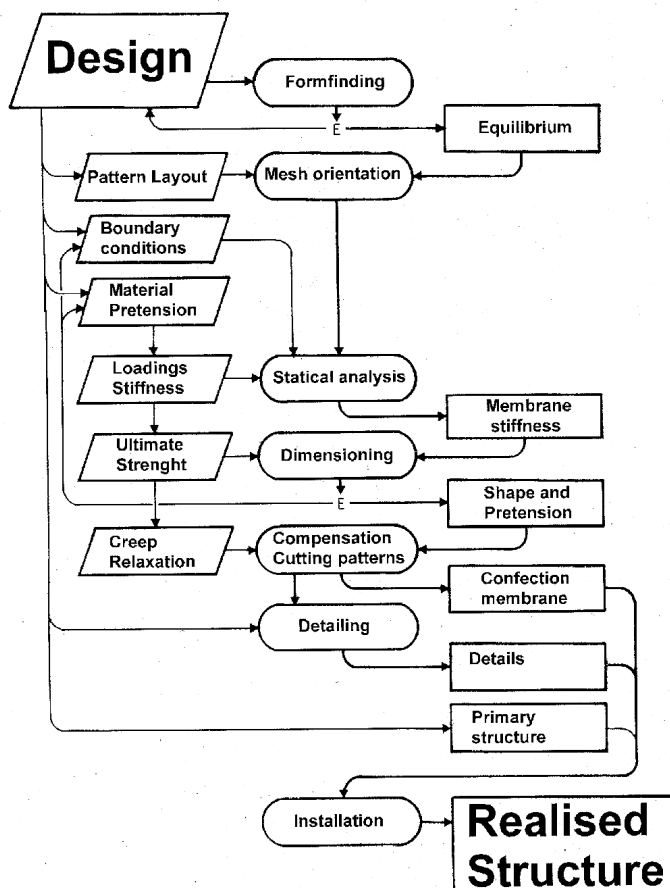


Fig. 8 Possible design scheme

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