MEng Membrane Lightweight Structure

Welded Strips as Reinforcements to Improve Membrane Structures

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Affidavit

I, **LORENZO SPEDINI**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Welded Strips as Reinforcements to Improve Membrane Structures", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

The field of this master thesis has high relevance in matter of new technical improvement design. This specific research field presents very limited existing literature. The subject of this research is to demonstrate that there is one new system to increase the stress resistance of a PVC coated polyester fabric membrane besides the well-known restraining techniques using steel cables or textile belts. This new system uses strips of the same off the shelf PVC coated membrane material welded in key locations over the main membrane cover. The application of this solution can also be for new architectural surface texture views of a membrane structure. The application of same material reinforcement strips as restraining bands for higher stress strength gives many technical advantages respect to the existing technology in terms of economical and mechanical performance. Also using this method it can be reached a better aesthetical look thanks to the elimination of the restraining steel cables substituting them with membrane reinforced strips having the same colour and finishing of the main cover. One outcome of this research is to create a new way to produce big covered membrane surfaces that can have already welded in the restraining reinforcement system. This new technique allows relevant costs savings compared to the existing reinforcement systems for both price of the materials used and for the great reduction of man hour time in the installation phase. The present master thesis is giving new knowledge with practical testing data results executed building a new testing machine. The scope of the new testing device is to check the performances of the membrane and of all the reinforcement strips under a uniaxial tension load. The new testing machine is able to give the needed correlation between stress and elongation on membrane samples with dimensions one order of magnitude wider and longer than the ones used in the common uniaxial testing machines for this specific research field. This new construction system could also reduce all the risks of the tensioning of restraining cables and of the problems of friction between the steel cables and the PVC membrane due to the different elastic modules of the materials. The result of the present research is to show in clear tables and comments that it can be achieved the increase of stress resistance welding reinforcement strips of PVC coated polyester fabric of higher type grade over the main membrane roof. It is demonstrated that the new reinforced material is behaving mechanically as an higher grade stiffer and stronger membrane type. It is shown also the performance of this new combined material in matter of percentage of resistance increase compared to the single layer membrane. In the same way is defined the reduction of deformation under stress of this reinforced material that can be used to solve many of standard problems of roofs made in tensile membrane. The main one is the ponding effect given by the elongation of the membrane under the initial load of the rain and snow. Is also presented a practical method to define the optimal placement of the reinforced strips to increase the mechanical performances of the main cover.

Finally is examined the possible aesthetical effect of the reinforcements applied over well-known tensile membrane shapes.

AKNOWLEDGMENTS

I would like to thank Professor Rainer Blum for his constant friendly help and patience to let me understand all the mechanical and geometrical relations behind the mere physical testing realm.

I would also like to thank my wife Federica and my son Giulio for the patience which they had to let me study and for the nice time had together during the lecture sessions days in Vienna.

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CHAPTER 1

RESEARCH OF A NEW WAY

1.1 Introduction: Restraining and reinforcing a tensile membrane as a natural consequence of connection systems:

When we think about a textile of any material we immediately imagine the behaviour and aesthetical view as a flexible and homogeneous surface of membrane with or without paintings or patterns on it.

If we concentrate on the subject one second time with more attention we can imagine the more essential nature of the textile as a woven fabric with a warp and a weft or knotted like a carpet. That’s all we can imagine at a first glimpse and also that’s what even many people involved in the membrane manufacturing cycle imagine and consider during their daily designing of textile productions.

But when we observe the applications field and goods where the textile membrane are applied as a more or less important part, then we see that every textile must be connected with one other piece of textile or with some other material to retain the desired shape.

The ways to achieve this tasks are those most commonly used like stitching, gluing, clamping and welding. All this techniques of jointing pieces of membrane naturally create borders that behave in a more rigid way respect to the single layer membrane.

This effect of hardening the textile border, that most of the time is secondary to the main function of jointing two textile parts, happens for many practical reasons like the followings:

- increase of thickness of the same material, like in the case of welding or gluing or stitching. In those cases there is an overlapping of two or multiple textile layers jointed together to achieve the textile anchorage. The sum of multiple layers add multiple times the stiffness of that textile part that behaves more rigidly than the rest.
- from the need to add some extra harder materials as a rope end or keder with some stitching to fix the membrane in a more definite perimeter as in the fabrication of sofas skins or in most of the leather made objects.
- from the need to fix the membrane to a steel or concrete rigid structure that defines the membrane border as in the case of a metal clamping. In this case the textile is not the cause of the sharp increase of stiffness but it’s the strong anchoring device that “transform” the textile in something different.

This general aspect of the stiffening effect of all the many joining solutions existing for a textile membrane have been surely carefully considered by the majority of the membrane designers and studied in order to achieve the best shape and the best resistance.

But mostly the interest of the membrane maker has been concentrated on the ways to connect one piece with one other and not on how to use some of the same techniques to add more resistance to the textile even far from a point or connection line.

1.2 Examples of carefully designed membrane reinforcement systems in history

When the membrane has been used as a main material for flexible and temporary cover solutions, the attention of the user has been to obtain a desired and mostly fixed shape able to keep that geometry even in conditions where external forces try to change that shape.

In order to achieve this task under the action of wind or other frequently applied forces the designer arranged to increase the rigidity and stress resistance of the membrane in various ways.

Here we can just briefly list some well-known solutions applied in the centuries to achieve the desired results:

We know that already the first nomadic culture where using the stitched animal skins to make umbrella like tents where the membrane was moderately tensioned over ribs made by wooden poles. Still now is possible to see living examples of those primitive but still cleverly crafted solutions in the nomadic populations that moves around the Mongolian planes. [1]

From that design idea then more developed cultures created many tensioned solutions using woven textile membrane to make even bigger tents: as in the case of the Arabian and generally the half nomadic cultures that populated North Africa and all the Middle East where is also today used as home the well-known conical tents supported by wooden poles.[2]

In those areas of application the solution of increasing the rigidity and therefore the shape determination of the system with cables and ropes started to be used. The latter applied on the borders or even as ridge and valley cables creates the tension active parts of the cover and a double curved surface able to resist to displacement.

One different but also very important use of the membrane textiles has been the sail making for the boats. In that specific application the membrane where and are also actually mounted over the masts using ropes and cables to determine their borders and to restrain it in a controlled shape under the variable actions of the wind. From this field of applications derives also all the ancient use of the “velarium” as in Latin language the Romans where calling the shading “velae” [3] or stretched textile woven membrane tents to be used as shading temporary covers over houses and even extended amphitheatres like the famous Coliseum. Still this shading way is used in the south of Spain to keep cooler the streets of the towns where the tents are stretched between the opposite buildings along the narrow central streets.

In relatively modern times but still more than two centuries ago Messier Montgolfier wanted to pneumatically inflate a woven membrane with hot air.[4]

For that reason having to deal with a weak stress resistance textile and also the need to connect the “balloon” with a hanging wooden gondola, where the first flying man where standing, the French engineer and paper maker used techniques well known in the circuses and also sailboats field to add restraining ropes to increase the resistance of the membrane.

In the last Century the restraining cables where used to increase the resistance of the membrane under pressure with design that allowed the construction of mighty membrane structures with spans not even imaginable using normal rigid and heavy materials as steel or wood. To give some names and examples we can think of the giant flying Zeppelin or to the more prosaic and commonly used pneumatically sustained tennis fields, swimming pools and stadium covers.

But we know also thanks to the visionary activity of our freshly departed mentor Dr. Frei Otto that using cables restrained membrane is possible to achieve covers of spans that are one order of magnitude bigger than any other man made structure and at least one order of lighter magnitude.

The one kilometre wide City of Artic [5] was designed by Frei Otto to be built in the middle of the Canadian artic planes under the commission of the Canadian government. The scope of such a great plan was to completely shield from the harsh local climatic conditions a complete city in which could live the people working in the nearby oil wells and mines.

Frei Otto envisioned the extreme point of application of the design of a huge pneumatic lens shaped cover using restraining cables knotted together to form a giant working net. This partially calculated structure was designed to discharge completely the tensions out from the membrane that becomes just a filler needed to make gas tight and weather tight the cable net cover that was able to keep the tensile stresses exerted by the positive pressure and also from the wind and snow loads.

1.3 Reinforcement systems in PVC coated membrane

If we restrict the research field on the PVC coated membrane, we can see that in the time a lot of systems have been used to increase the resistance of the membrane and they are substantially the followings:

Beam supported membrane

Rope/cable restraining system

Belt restraining system

Beam supported structures

In this category are intended all the covers provided with a rigid skeleton made by beams in steel, wood or concrete that form a fixed boundary for the membrane that is anchored to it. This vast field of covers and structures will not be investigated in this research for the fact that the membrane is used only to close the spaces between the beams and not to retain the stresses as in the following categories.

Rope/cable restraining systems

This category is by far the most used system to increase the resistance of the membrane that is more or less working under tensile only stresses.

There are vast differences of mechanical properties of the cables and of the ropes (the latter used in the smaller projects) and there are quite many shapes and uses of the restrained covers that can be designed.

For this reason is possible only to generally define some positive and negative qualities of this technology application learning from the past realizations.

1.4 Cables performances

The first quality of the cable, intended mainly as steel made, is to be able to achieve with lightness very high stress tensile tension resistance with low deformation in elongation compared with more rigid and heavy structures. This peculiar mechanical characteristic makes the cable as the apparently simplest solution to achieve a greater resistance with a tensile stressed membrane.

The cable can be coupled to the membrane with the insertion in membrane made pockets or simply placed over or under the cover to create ridges and valleys or connected with local bolted points spaced along the membrane in the direction of the membrane border. The much greater Elastic module of the cable respect to that of the membrane makes the cable a stiffer uniaxial element connected to an elongated biaxial element. The effect is that once a membrane under tensile stresses is connected to a steel cable, it will discharge much of the tension load on this linear element due to the higher stress resistance and lower elongation the cable.

Due to the uniaxial direction of the cable this effect of membrane stress unloading will be prevalently achieved in the direction of the cable where the membrane that pushes against it discharges a good part the load. As a secondary effect, seen specially in pneumatic covers, the membrane that is partially unloaded changes his geometry creating areas with smaller curvature radius between two adjacent cables thus decreasing the working stresses even on the opposite direction.

The membrane size must be carefully designed in a way to have a geometrical extension under tension longer than the cable length otherwise it would be impossible to obtain the membrane unload effect over the cable system.

The figure below shows a stress analysis example of a pneumatic pressurized cover with cable restriction compared to one made with simple membrane.

The form finding in figure 1 and 2 (without caring about the specific loads and resistances applied in this examples) has been made with the Technet Easy Vol software that simulates the membrane physical behaviour under tension stresses.

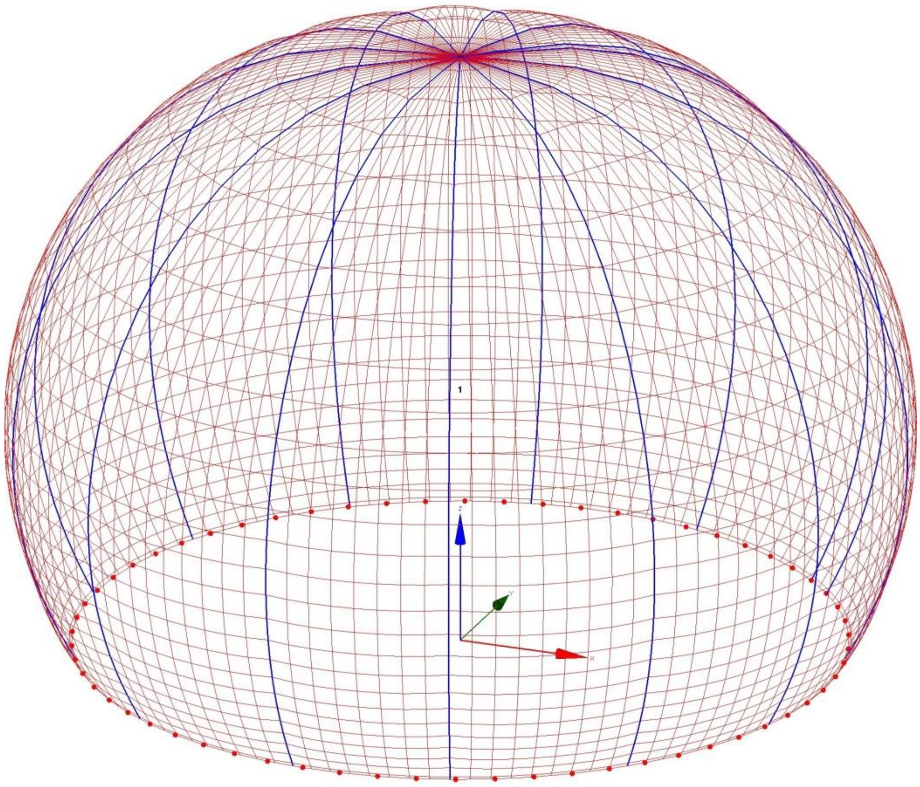


Figure 1 with pneumatic cover cable restrained shows the different curvature of the membrane that is elongating more respect to the cable (shaped like a pumpkin) due to the lower stiffness of the polyester fabric

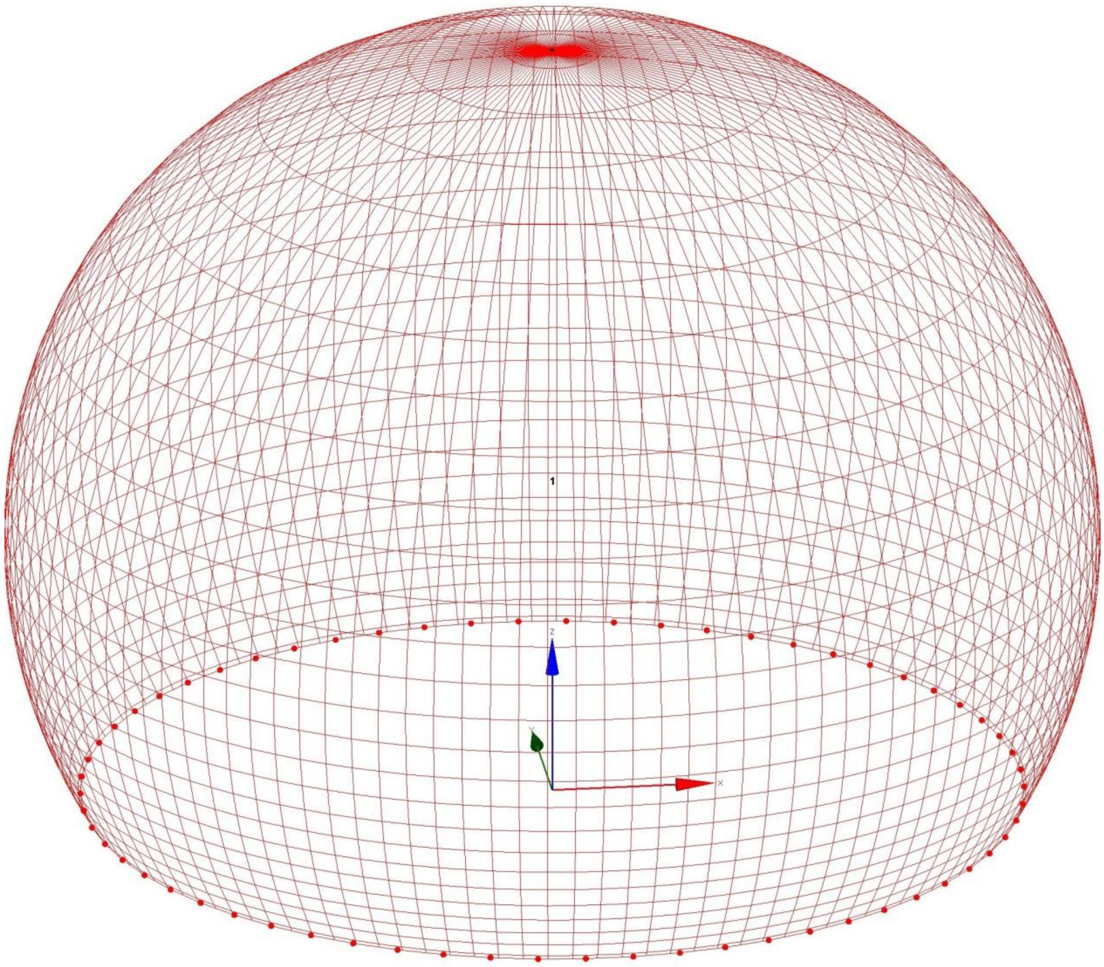


Figure 2 of a simply pressurized cover where the membrane is acting homogeneously with a simple and constant curvature radius and stresses equally distributed in warp (with warp direction vertical from the floor plane in this example).

In pneumatic controlled covers the best achieved result is by the application of a restraining cable net over the membrane so that all the loads are biaxial (in both warp and weft directions) equally supported by the steel net.

Cables limits:

There are unfortunately many factors that limit the performance of this restraining technique in terms of duration and also of economy of the solution:

On the pure mechanical point of view the very different nature of the steel cable respect to the PVC coated membrane is the cause of most of the problems.

In fact the greater cable stiffness makes a constant small sliding effect between the more deformable membrane and the steel cable thus creating an abrasion effect that can cause with the time the cut of the membrane directly underneath the cable. This sliding effect is made by two main causes, the constant differential displacement due to external loads effect like wind or snow that constantly changes the cover geometry and the thermal dilatation that elongates differently the steel cable from the membrane causing constant small movement of one material over the other.

The fact that the cable is made by many thin steel rods creates often problem of damage when after some time one of the external rods breaks and peel off the cable puncturing the membrane.

The steel cable even if made with the much more expensive stainless steel version loses rust and lubricant that will stain over the cover without cleaning possibility due to the fast chemical bonding between PVC and the steel components.

One more negative effect is that steel cables for the high applied stresses must be connected to some strong concrete or steel foundations on ground. The ground connections together with the cable high conductivity creates a good earthing of the cover. So in case of thunderstorms the risk of the cover being struck by a lightning is great due to the presence of such long and highly located conductive cables that will get down to earth the big electrical current of the lightning with the risk of cable overheating and then to melt the PVC membrane in contact to it.

The use of so highly concentrated tensions is a real potential of possible catastrophic damages due to a sudden rupture of a cable or of a cable fixing end that can cause the immediate fly of the cable in the direction of the tension force with a whiplash effect that could easily make big potential damages to almost any material and also humans eventually standing in the cable path. So there must be placed more attention to the hazards of the cables presence in the design phase in order to mitigate those risks.

Finally but not least important is the economical high cost of this solution for the following reasons:

- Cables are very expensive to manufacture and there are not many steel cable producers on the market and this market concentration surely doesn’t help to limit the prices.

- The cables need a series of special very expensive metal fixing edges that have to be carefully designed and prepared on every specific application.
- The use of specific high grade and limited production cables needs expert designers able to correctly size and also talk to the cable manufacturer to order the right cables cut in the right length. That is of course quite expensive and only in big engineering companies specialized in big construction buildings there are the right economics to have such an expert figure.
- Finally there are big costs for the need to correctly install the cables of the membrane cover on site due to the complexity of the cable insertion in the prepared pockets or joints on the membrane and for the great time spent to carefully pre-tension the steel cables to correct the final shape of the membrane.

1.5 Belts performances

The use of belts instead of the steel cables has been less used for big span covers and generally less commonly applied.

Belts are generally made with textile woven fabrics hereunder listed in crescent breaking point resistance:

- cotton
- polyester
- polyethylene
- polypropylene
- nylon
- aramid fibres

Besides the different stiffness due to variable manufacturing nature construction parameters like fibre materials, weaving type, thickness, belt width etc.. the belts have common performances qualities:

They are flat and almost two-dimensional and so more easy to be coupled with a membrane.

They are less strong then the steel cables but they can be much stronger than the PVC coated polyester membrane.

The textile woven nature makes the belt more close to the membrane nature with the results of creating less kinks and more gradual loading of the belts with comparable but smaller elongation needed for the load discharge of the membrane. This eliminates most of the possible problems of too specific punctual action of the steel cable.

Made in plastic polymer they can perform under the fatigue action more alike the tensile fabric of the PVC coated polyester fabric and so they can better follow the deformation cycles of a tensile membrane.

There are no special negative effects as staining or cuts provocation on membrane thanks to the absence of sharp points on the belts.

They can be stitched directly to the membrane thus eliminating the complexity of fixing of the cable.

If the belts are small they can also be prepared stitched or even welded in some cases directly on the membrane in the shop eliminating the need to insert them on the installation site with much less costs. See picture hereunder

Picture 1. View of a conical PVC membrane cover under welding at the author production shop with workers finishing the hot air welding of PVC coated belts over the main cover membrane

Belts limits

Due to the great variability of materials and weaving systems, the belts mechanical characteristics are quite changing depending also from each producer ability. This difficulty of defining the real working performances of the belts greatly reduces the appeal to the membrane designers that in case of belt choice they have to make their own testing measurements.

Confronting this complexity to the steel cable we can see that the difference is big where the mechanical performances of the steel cable are well communicated by the producers with nice and exhaustive technical charts.

Even if it is possible to weld 20 to 60 mm wide PVC coated polyester belts directly over PVC coated membrane it mustn't be considered as a mechanical working bonding but just as a way to pre-install the belts on the membrane.

This weak welding is due to the poor anchorage of the PVC layer on the belt thick textile and also to the high stiffness of the belt respect to the membrane that causes the self-detachment of the belt from the main membrane cover due to the shear force action between the two materials. This detachment also leave the membrane underneath without the coating and that means the loss of the nominal lifetime of the PVC coated membrane and of the water tight effect.

Picture 2 View of the conical shaped cover centre with all the belts ending in a stainless steel buckle to be bolted to a steel central anchoring flange placed on the top of a steel central mast. It can be seen the high complex work of the technician that has to carefully connect all the edges of the belts in the right position in order to correctly execute the bolting in the right places.

Even if the belts can be inserted in membrane pockets so they can be let free to move inside them, this work compared to the simple welded membrane need more fixing labour and preparation before the installation together with the folded membrane.

The relatively great thickness of the belts compared to the membrane makes some problems of bulky masses that complicates the folding procedure specially in case of big covers with the consequence of increasing of working time and the costs.

The belt coarse textile nature and also the belt's pockets are one cause of dirt and stain accumulation and of maintenance need.

Even if the belts are more close in nature with the membrane they have to restrain, still there is some sliding effect due to their big stiffness specially in the cases of strong and thick belts like the ones used for the heavy material lifting.

The sliding movement creates a friction against the thin PVC coating with the risk of removing the PVC protection from the textile and then with the loss of most of the mechanical resistance of the uncoated membrane.

It can't be coloured as the PVC main membrane thus making impossible to shield it from view.

In case of direct stitching of the belts over the membrane there has to be clarified that the stitching is not a good solution form keeping the water tightness due to the fact that it makes small holes though the PVC coating. The action of the stitching wire also diminish the resistance of the textile due to the fact that it punctures the polyester fabric breaking some of the fibres.

1.6 Membrane strip reinforcement as a new third way

The scope of this research is to show and calculate the good and the bad sides of a newly applied solution idea, that is to use as a reinforcement belt-like strips cut from off the shelf polyester PVC coated membrane to be welded directly on the main cover.

Membrane reinforcement good performances

Due to the novelty of this solution, that may have been already applied by some manufacturer but of which there is not available data, we can guess only the main point of strength and weakness of it. We will be able to confirm the effectivity of this solution after the following tests that will be presented in this master work.

Basing on the personal experience as a membrane designer and membrane tensile product manufacturer the author can set with knowledge the following benefits of the application of the present solution object of study:

Thanks to the same material nature of the main PVC cover it can be increased the stiffness value of the membrane and also the breaking point without having problems of extreme differential elongation between the reinforcement strip and the main membrane as in the previous solutions.

For the previous mechanical reason there is absolutely no possible harm caused by the accidental rupture of one of the reinforcement strips even close to the dangers that a tensioned broken belt or cable can cause.

It can be done on any size cover without increasing too much the costs of material handling or order tasks while that is not true with the steel cable and less important for the belts. So this solution can be a good way to upgrade the strength resistance or the stiffness of even small and relatively inexpensive covers without the need to upgrade the quality of the overall membrane type.

As it already is done for the truck tarpaulin manufacturing the presence of multiple parallel reinforcement strips act as a cut propagation breaker in case of a membrane damage. In fact in a tensile membrane if there is a cut it will tend to propagate at increased breaking speed until it does meet something more resistant that will stop or greatly reduce the speed of the cut and thus diminishing the impulse energy that keeps otherwise to cut the membrane fibre after fibre driving the propagation to a stop.

It has to be clarified that surely it will be impossible to entirely substitute the use of steel cables in extreme loading conditions but it can be done in most of the lower working cases at the loads that are more close to the one supported by the single membrane.

This system gives the possibility to increase the overall safety factor of the specific membrane type used for the cover with the aim to elevate the resistance of the welding from the standard 70-80% to the 100 % of the breaking point of the membrane. This effect can be enhanced if the welded reinforcement strips are placed laterally near the main welding in order to unload partially the welding itself.

Besides the mechanical engineering qualities this new technique can be visually an act of lightness if compared to the other solutions as above.

It can be deliberately chosen by an architect either for the need to completely masque the reinforcements from the view using the same membrane colour of the main cover or even made to be well seen using different colours or variable reinforcement shapes that surely can’t be achieved with the precedent methods.

There are no problems in folding after production and during installation. Everything is already in place and ready to work together with the membrane.

On the installation tasks there is no need to execute any pre or post tensioning of the reinforcements due to the fact that they are already welded to the cover and so the effect on it will be done by the higher stiffness values that will be directly applied distributing them on the main membrane surface. The only main care will be to keep connected the reinforcement edges to a strong anchoring device to avoid breaks.

The production times even if longer respect to the sole membrane manufacturing will be much shorter if compared to the times spent for ordering and awaiting the arrival of the cables from third party producers maybe even located in different Countries.

It can be done in the same methodology of the rest of the welding with the standard caution that has to be made when using too high thicknesses or to many layers and too different fabric types.

This system is working at his best performances when the reinforcement are executed with high frequency welding. This semiautomatic welding method gives the following advantages over the hot air systems:

- it gives high reliability and repeatability due to the machine controls of the welding parameters
- it helps to better fuse together the PVC overlapped layers with the use of the high pressure applied on the welding electrode
- thanks to the use of the High Frequency electric field it is able to heat only the polar molecules of the PVC from the inside without overheating the working fibres of the polyester. This helps to keep the mechanical resistance values of the polyester textile unchanged while the hot air heating system tend to reduce them.

Membrane reinforcement limits

The main limit of this new solution is clearly set looking at the specific tension resistances of the even highest reinforcement membrane type (as T4 or T5). Those breaking point tension values are 20 times weaker than the normally used steel cables and even 5 to 10 times weaker than the good size belts actually on the market for the use in weight lifting. So it’s impossible to completely discharge the working main membrane from much of the stresses while in the belts and cables this is a normal positive effect.

There is also one other economical limit to this solution that is given by the cost manufacturing increase if the number of parallel welded reinforcements is too high. This means in other terms that if there are too many reinforcement strips to weld one near the other closely spaced then the best solution and also the cheapest one is to directly upgrade the complete membrane type of the cover for example from a T2 to a T3.

The thinner reinforcement membrane also can be subject to a faster degradation by the weathering effects and by the action of UV rays respect to the belts or cables.

This matter may be not so important because when the reinforcement strips will reduce too much their mechanical resistance also the main weaker and thinner membrane of the cover will suffer from the same damaging actions even before.

There is also a limit in the material choice of the reinforcement strips when that is deliberately reduced to the off shelf products in order to maintain the low cost of the solution. For example it could be even ordered a Type 6 membrane but it will be never found off the shelf and even it will be needed a lot of time and efforts just to find one producer able to make it and then it’s back the problem like the one of the specialized steel cables short list of suppliers.

1.7 Scope of the research

The main scope of the present research is to demonstrate that is possible to combine the functionality of the belt reinforcement system with the same nature of the membrane applied for the cover to obtain a new and easy to apply restraining system with membrane made belt reinforcement welded-in.

Possible outcomes expected from the research

Defining the right combination of membrane reinforcement needed to weld over a PVC coated membrane to achieve a stiffer and stronger cover.

Understanding the limits of this solution made using only standard off the shelf tensile membrane products and application of them as same nature belts with a specific width to be welded with high frequency method over the warp main direction.

Evaluation of the possible costs of this system compared to a only membrane made cover.

After the testing also we can observe the reinforcement solution as a new way to influence the architectural aesthetical appearance of a membrane cover look, with new patterns and color changes and 3D prospective enhancement.

Research methodology

In order to know how the reinforcement can work over a PVC membrane the author followed a specific path designing and manufacturing for the specific research scope a new uniaxial testing machine that could give the comparative values of the results in terms of breaking tensile strength compared to the material elongation.

Before defining the machine working boundary and proprieties the first step was to check the maximum and minimum stresses working field of the standard membrane types from 1 to 5.

Then it has been chosen the size of the samples to test under the stress limit constraints and the need to make the dimensions of the samples as close to real dimension as possible. The size of the sample depends from the width of it and from the width of the membrane belt reinforcement.

Due to the fact that in the author shop it was possible to reach a maximum welding width of 9 cm with the available High Frequency welding machines and also because the best welding practice also commonly found in the technical literature [6] [7] recommends that a welding width of 80 to 90 mm is the one needed to achieve the best adhesion results.

Also we need to get a wider reinforcement strip respect to the common textile belt widths due to the intrinsic weakness of the membrane respect to a reinforced different nature belt.

CHAPTER 2

A NEW TESTING MACHINE

2.1 Designing and building the testing machine

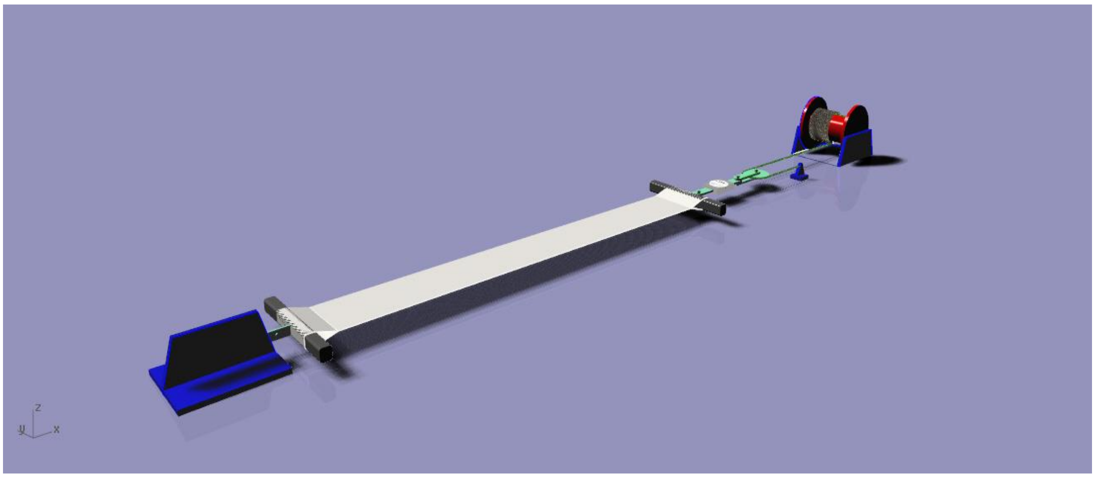


Figure 3. Full prospective view of the testing machine draft plan. Drawing made by the author using Rhino5 3D drawing software

From the basic research of this specific type of material the best testing machines available now are the biaxial tensioning machines that work to check the relation between tension stress and deformation happening in both directions in the same geometry field of the membrane that has a two dimensions nature of a plane.

The tensions applied in those machines are within the normal "elastic" behaviour of the membrane meaning that the tensions applied does not go up to the breaking point of the membrane.

In the research the author wanted to focus on the matter of reinforcing a membrane with a belt like structure that works only in one main direction. The stresses are going to be checked not only in the standard working load field of the membrane but also up to the breaking limit. So it has needed to think to build a specifically designed uniaxial testing machine.

The uniaxial testing machines used typically to test the samples of the membrane under the DIN and now UNI EN standards check the relation between tension and deformation of a 5 cm wide sample. That is a good and example to test the breaking point of a single layer membrane with relatively predictable and repeatable results.

But in this new design we wanted to enlarge the testing width up to 50 cm or even 1 m in order to test in a much more realistic environment the work of the membrane also adding one or more 9 cm wide reinforcement belt.

In order to have a straight and relatively slim sample and to be able to manufacture a testing machine within the working space available in the production warehouse it was chosen to multiply by 8 times the width of the sample to have 4 m length on the unstressed sample in warp direction.

Then the length of the machine run was sized to be longer enough to keep pulling the sample while the sample is elongating by at least 30% of his initial length so it was defined 5 m for the maximum elongated sample.

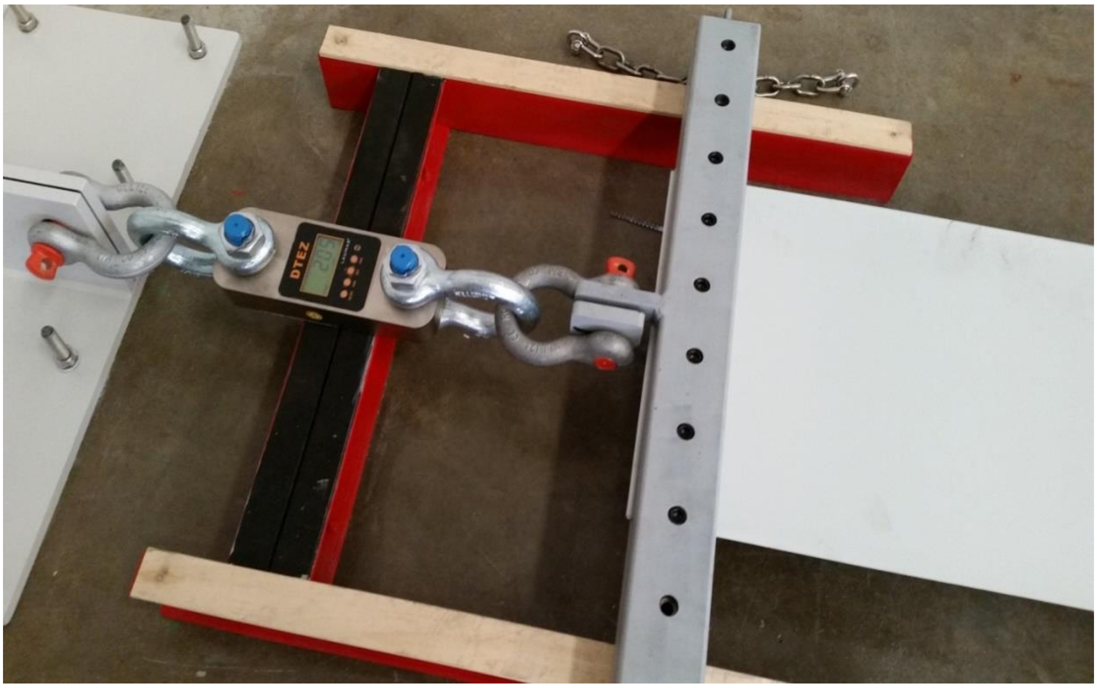
At the end this machine is able to test a size of sample that is in a scale of 1:4 1:6 respect to the max membrane width. That is 10 times bigger than the usual testing machine samples and for that reason is 10 times closer to the real size of the material. And even in this field size matters. Adding all the traction components the machine has a total overall length of 7,5 m.

It will be expected to have more errors in the testing procedure due to the higher grade of un-homogeneities in the sample preparation and anchoring to the machine that will surely reduce the break point of the materials respect to the values tested in the 5 cm wide samples. But even if the results will be not as precise and repeatable they represent a much more realistic description of a membrane under stress at the limits.

2.2 Calculation of the max tension stresses needed to be performed by the new machine

The maximum calculated stress is an equivalent to a T5 membrane 50 cm wide sample that at the breaking point needs 100kN = 10 T to get to that limit. In order to be able to measure the traction applied force to the system it has been inserted in the testing line a dynamometer able to work up to 10 T with a sensibility of +_ 1 kg.

Due to his existing working experience the author have chosen a weight cell type dynamometer that has the nice quality to measure accurately the pull force without elongating towards the force line and so eliminating all the possible needs of steel cables and pulleys on that side.



Picture 3. View of the testing machine dynamometer connected on the right side to the steel flange and on the left side to the anchoring fixed tension reaction flange bolted to the concrete ground.

Once defined the design maximum stresses criteria and the size of the sample to test we proceeded with the research of an adapt pulling system to achieve the desired working limits. It was found on the market an Italian manufacturer of puller or winch that use the simple leverage of Archimedes to pull up to 5 T with the sole force of the human arm.

The winch steel pulling cable has a diameter of 22 mm and was calculated to have a safety factor of 2,5 with a max allowed load of 12,5 T. Having to get up to 10 T it was just kept the same working leverage principle and it was bought a closed edge steel pulley able to double the traction force up to 10 T.

See the attached design scheme figure in the next page.

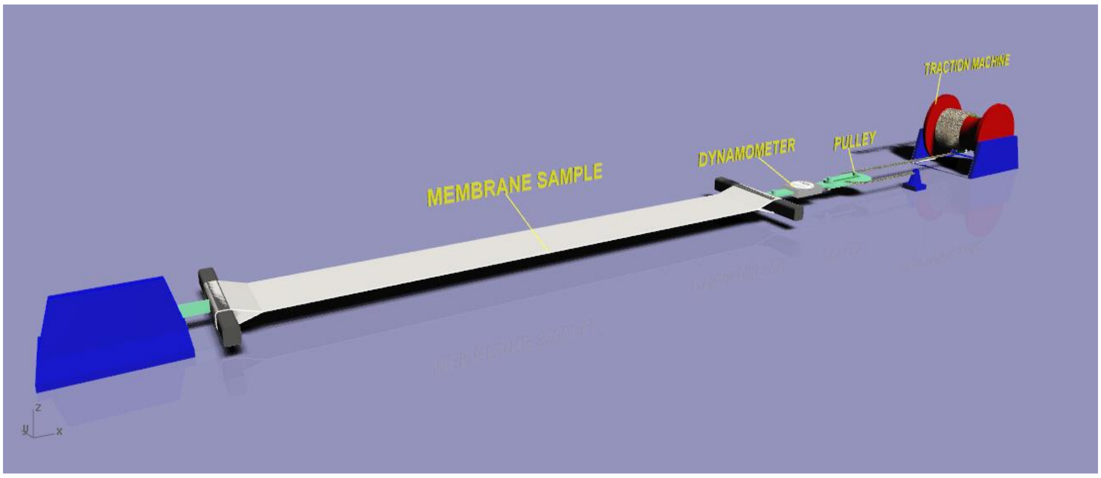


Figure 4. View of the 3D draft full design of the testing machine. Note that the location of the dynamometer is placed in the side that moves under the traction of the winch. This location was later moved to the other side in order to eliminate the dangers of moving the sensitive dynamometer during the elongation of the sample under tension force

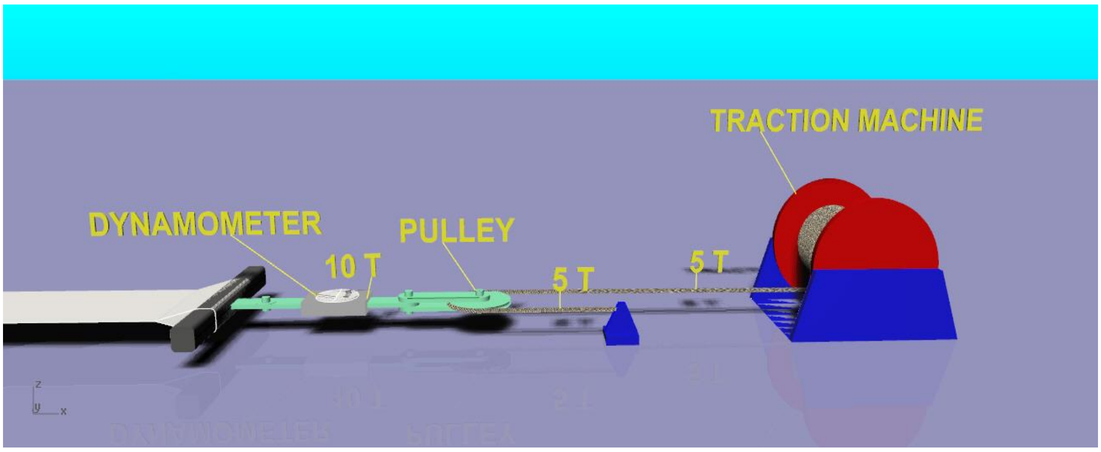
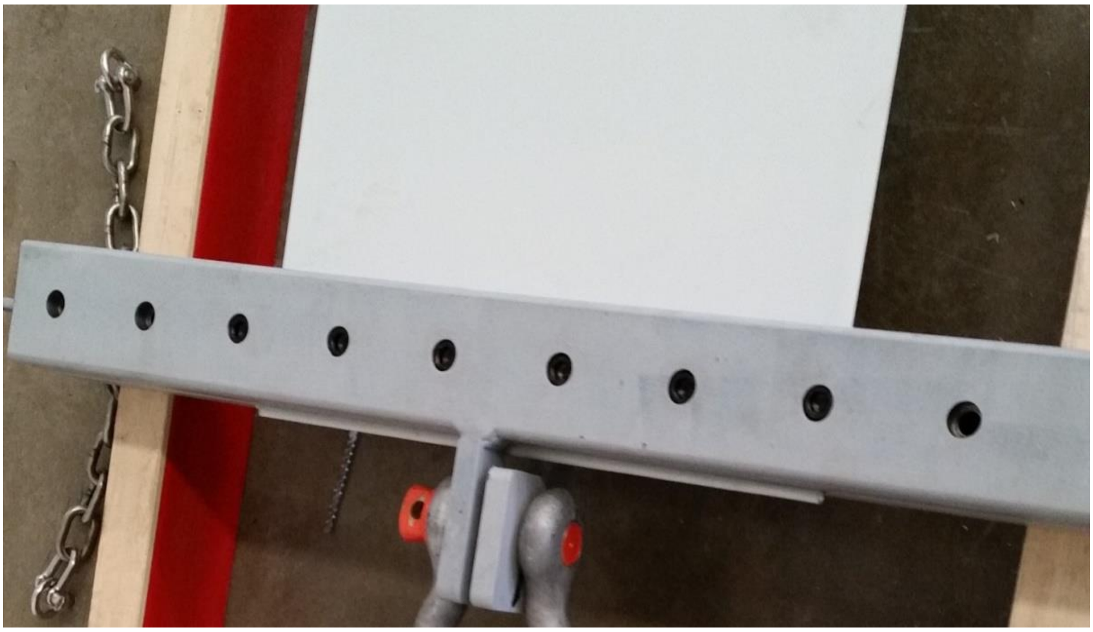


Figure 5. View of the 3D draft testing machine scheme with the max applied design tension forces

2.3 Defining the anchoring beams

The test sample to check is a bolted membrane with a keder as safety pull back stop system. The keder used for the safety part has been a 6 mm polyester rope that is quite slim so that the membrane can be welded around it as it can be seen in the picture 4 but that due to his relative rigidity will never be deformed to the point to slide inside the flange.



Picture 4. View of one of the two membrane sample anchoring flanges

It could have been used a system with unbolted keder like in figure 6 that can achieve surely better resistance of the membrane close to the break point due to the absence of the holes punched in the membrane that are a major point of weakness and a sure propagation of a cut on the membrane. But doing that we would have achieved a non-usable test due to the fact that for practice and costs is more commonly applied and easy to produce a bolted flange like the system as in figure 7.

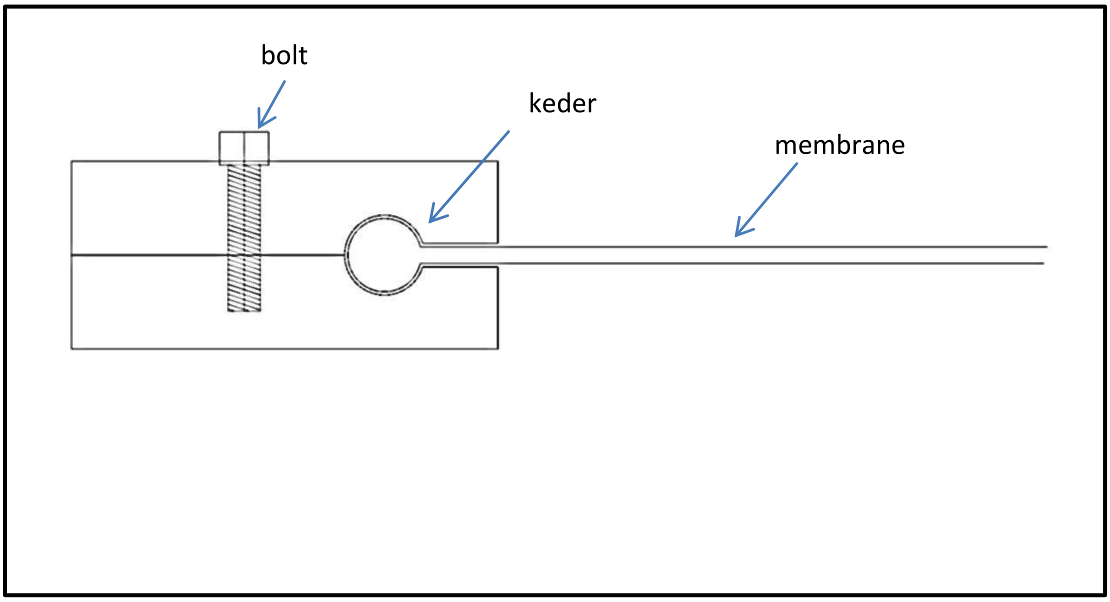


Figure 6. Keder non bolted flange system with the closing bolt external from the membrane without the need to punch holes that will diminish the active section of the tensioned membrane

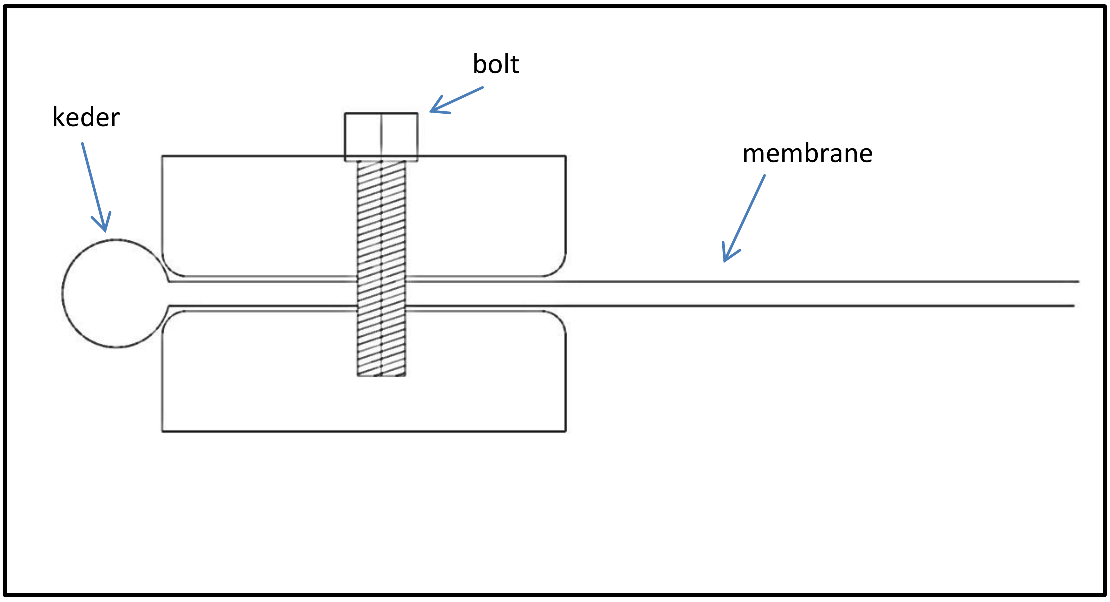


Figure 7. Keder with bolted flange system with the closing bolt that passes through the membrane with the need to punch it.

Anyhow, in order to consider the flange sufficiently strong and resistant respect to the force applied on the bolted enclosed membrane, the two fixing flanges where made very stiff so that they would almost not bend under the 10 T max pull force. So the flanges have been made from solid black steel rods with the section of 100 x 50 mm.

To eliminate every sharp turning point and edges of the anchoring system all the corners of the steel flanges have been chamfered with a radius of 10 mm as in picture 5.

Picture 5. View of the smoothed section of the anchoring flanges and of the safety steel flaps placed underneath the moving flange to let the bolted profile slide over the steel railings without the risk of moving randomly at the time of the sample test breaking point.

For the sake of the symmetry and due to the existing bolt pattern commonly used in the standard European flanges it was chosen to have a distance between the bolts of 100 mm and using bolts of 14 mm thread.

The number of holes which will have the 50 cm wide membrane once bolted under the fixing flanges is 6 times 16 mm (16 mm is a 2 mm wider diameter hole made for the need to punch the membrane in a way to be able to insert the bolts trough the membrane sample) equal to 96 mm of not working membrane.

This is in effect what happens in the reality when there is an anchorage profile for a bolted membrane. In this case having a sample of 500 mm width and having a missing punched membrane area of nearly 100 mm we have an expected reduction of stress resistance by a 20% factor. It means that all the measured values from the tests will have to be compared to the breaking strength of the membrane adding a $1/5^{th}$ more strength to the results from the testing machine.

The closing force of the bolts has been 40 to 50 kN*m applied with an automatic fastening machine. This closing force is the one indicated by most of the bolts manufacturers to achieve the best closing action with a bolt of 14 mm in diameter.

To see the elongation of the membrane under the applied tension force it was simply placed one mm scaled meter steel roll parallel to the support rail of the moving flange so that it could be seen how many cm it moved from the untensioned status. See picture 6.

Picture 6. View of part of the testing machine moving anchor flange that slides over the red colored rails coated with a smoot wooden top. The metric long metal ruler that serves to measure the sample elongation under the tensile force can also be seen.

2.4 Safety measures for the testing environment

Without knowing the amount of energy released in a fraction of a second from the sample once tensioned to the break point and also without knowing the real possibility of ballistic of any of the machine parts subject to the huge traction force it has been designed the system to work in a status of safety adding a series of countermeasures and protections:

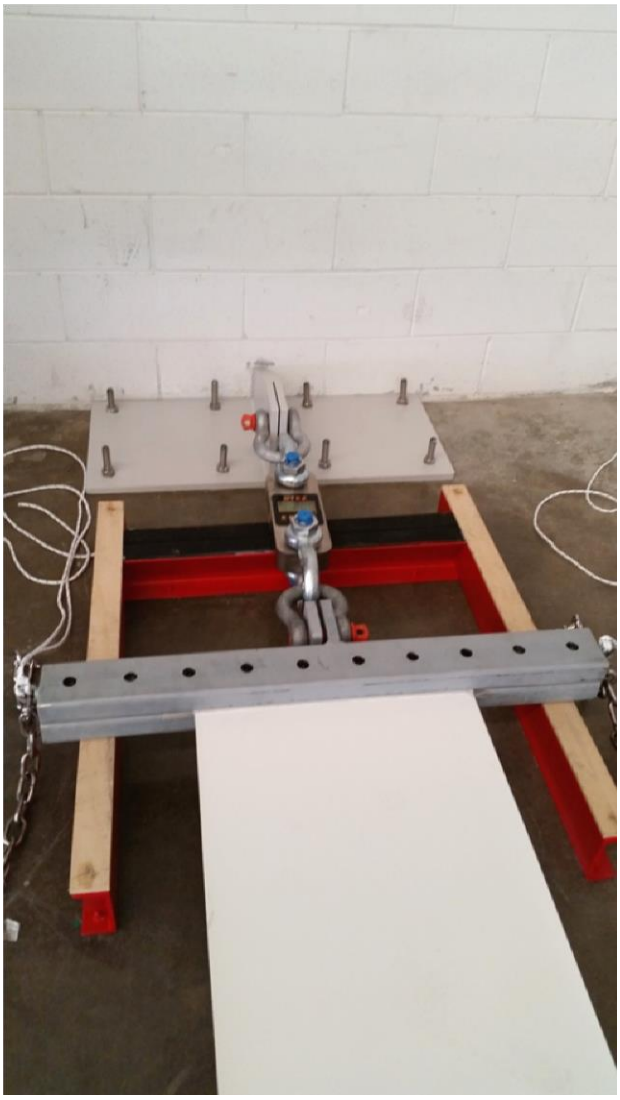
First of all even for the easiness of the system it was chosen to direct all the pulling force horizontally at 20 cm from the ground. In fact being low from the ground it reduces a good part of the possible dangers given by torsion moments and bending moments acting to long connecting arms. Also it limits the risk of elastic re-bouncing of the sample test membrane and of the eventual flying parts related to the testing sample.

Picture 7. View of the manual winch able to execute a max traction force of 5 T

It has been set a screen made in steel mesh of 40 x 40 mm x 4 mm thickness to protect the tester from being hit by the broken sample while pulling the winch. For the same reason the main walkway of the pulling beam was covered with a carter like box in the same steel mesh to protect even from the far consequence of a break in the steel cable anchor.

Picture 8. View of the full testing machine on the side of the winch. All the safety steel mesh protection screens can be clearly visible.

To avoid also the risk of a fast and uncontrolled movement of the anchoring beam located to the other side respect to the winch location (even if due to the huge weight of it, around 50 kg, it wasn’t expected any fast and long range slide) the flange was connected with a short steel long chain that would immediately stop the slide of the beam after few centimetres.



Picture 9 View of the machine side of the fixed anchoring membrane flange not subject to the sliding effect of the other side. Here the location of the dynamometer and of the main traction force discharge flange close to the wall can also be seen.

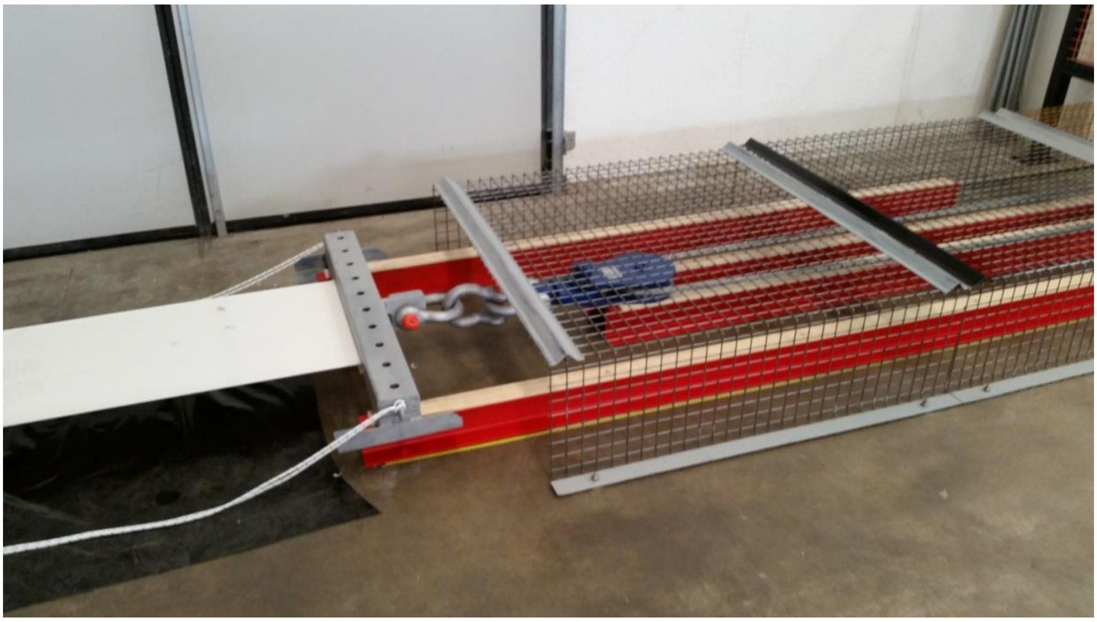
It was bought also a clever and safe radio command for the dynamometer that can show the pull force at even 30 m distance from the weight cell position so that the testing person hadn't to stay close in the line of the tensioned membrane sample in order to see the results on the direct screen of the dynamometer. This system also allowed two or more people to assist to the sample testing from two different positions still being able to read the tension force values. See picture 10 and 11.

Picture 10. View of the dynamometer radio command with distance screen tension checking system

Picture 11. View of the dynamometer connected to the big shekels

To reduce the possible wearing of the moving components of the machine and mainly the heavy pulley of the steel cable and of the moving membrane anchoring beam there was set a series of steel railings covered by smooth wooden plates that work in multiple ways. The main task is to support the pulley and the traction anchoring membrane beam so that both items are always at the correct height of the pulling phase without having to touch the ground or to change height during the testing procedure.

Also the moving membrane anchoring beam is sliding underneath the profile of the rail with two steel flaps that prevent the beam from rolling around once the tested membrane is torn up and releases his energy in a shot but it allows only to slide along the railings direction without harming anything around it.



Picture 12. View of the rails to allow the correct sliding horizontal movement of the anchor flange and also of the pulley movements.

Picture 13.In the centre is visible the blue coloured steel cable pulley

Machine location

The author had a good spot in his Company workshop with a clean, smooth and solid concrete surface were it could be drilled all the fixing steel plates needed to anchor al the main parts of the machine.

That area could also easily be limited to the access of unauthorized personnel so that the safety of the zone during the test phases could be increased.

Defects of the machine

While the machine did perform as planned in a way that outperformed the needs from the design it’s also to say that this machine presents a little number of missing ancillaries that would make it much more easy and fast to use. The following are the possible components that could be added (and most probably will be added with the time) to the existing configuration to help the user:

Add a pulley system to unfurl the pulling movable flange once it has moved from 4 m to almost 5 m respect to the fixed flange side once the membrane sample traction test has been done.

Now due to the high weight of the beam plus the weight of the huge steel cable it needs the force of two people to pull back the moving sample flange back in the position zero generally one meter away from that initial location.

Add a motor to the axis that is now rotated by hand through a lever in order to eliminate the good amount of human energy (and a good amount of healthy exercise for the tester person in charge of pulling the sample to forces higher than 4 Tons)

Add a fast motion track video camera to record the moment of the sample breaking point and to better understand the starting dynamic of the point of failure of the membrane.

Add some extra protection safety nets to cover the tested sample from accidentally hitting the person in charge of assisting to a welding sample breaking standing near that location.

CHAPTER 3

TESTING SAMPLES DEFINITION

3.1 Testing the samples

Here is showed the complete list of all the testing that have been made on all the samples with membrane types from 1 to 5 divided by type of the main testing sample of 500 mm width.

Here the combination of testing actions:

a) 50 cm width T1 alone, T1 with 9 cm T2, T1 with 9 + 9 cm T2, T1 with 9 cm T3 (= 4 Tests made)
b) 50 cm width T2 alone, T2 with 9+9 cm T2, T2 with 9 cm T3, T2 with 9+9 cm T3, T2 with 9 cm T4 (= 5 Tests made)
c) 50 cm width T3 alone, T3 with 9 cm T4, T3 with 9 cm + 9 cm T4, T3 with 5 cm T5, T3 with 5+5 T5 (= 5 Tests made)
d) 50 cm width T4 alone, T4 + 9 cm + 9 cm T4, T4 + 9 cm T5, T4 + 9 cm + 9 cm T5 (= 4 Tests made)
e) Strips: 9T2, 9+9T2, 9T3, 9+9T3, 9T4, 9+9T4, 9T5, 9+9T5 (= 8 Tests made)

In order to execute the full set of testing it has needed a total time of 15 working days. It has to be remembered that for every sample tested it had to be done the following testing methodology.

Testing methodology

The testing has been made in a fair simple scheme that is defined with the following action series:

1. Fixing the membrane sample to the anchoring flanges on both sides. In order to execute correctly the fixing it has been made a template to increase the precision of the punching of the holes on the membrane for the bolting.
2. Setting the zero on the elongation axis moving the mm scaled rule to the starting position of the moving flange
3. Setting the zero on the electronic dynamometer
4. Start pulling the sample to the achievement of the tension = example 2000 N proceeding with steps from 2 to 5 kN.
5. Once the sample has reached the desired tension value read the elongation in cm on the mm scaled ruler located near the rail on the ground.

6. Write the values in a paper chart with force in kN and deformation in cm
7. Proceed with an increased pulling force on the sample following the steps as in “test T3 not bolted” hereunder or “ test T1 bolted” in case of the lighter material samples.
8. The testing ends when the sample suddenly breaks and there is only to check the breaking point force while the deformation can’t be read in the same time by one testing person. It is also not so important due to the fact that it can be easily deducted by interpolation with the previous point of the curve kN/cm.
9. Pull back in place the moving flange
10. Unbolt and remove the used tested sample
11. Set to zero the residual kg values reading on the dynamometer

test T3 not bolted

T3 not	bolted
kN	cm
2	2
5	5
8	9
10	15
12	21
15	30
18	39
20	42
22	45
25	50
28	54
30	57
32	59
35	61
38	63
40	65
42	66
45	68
48	71
50	73

test T1 bolted

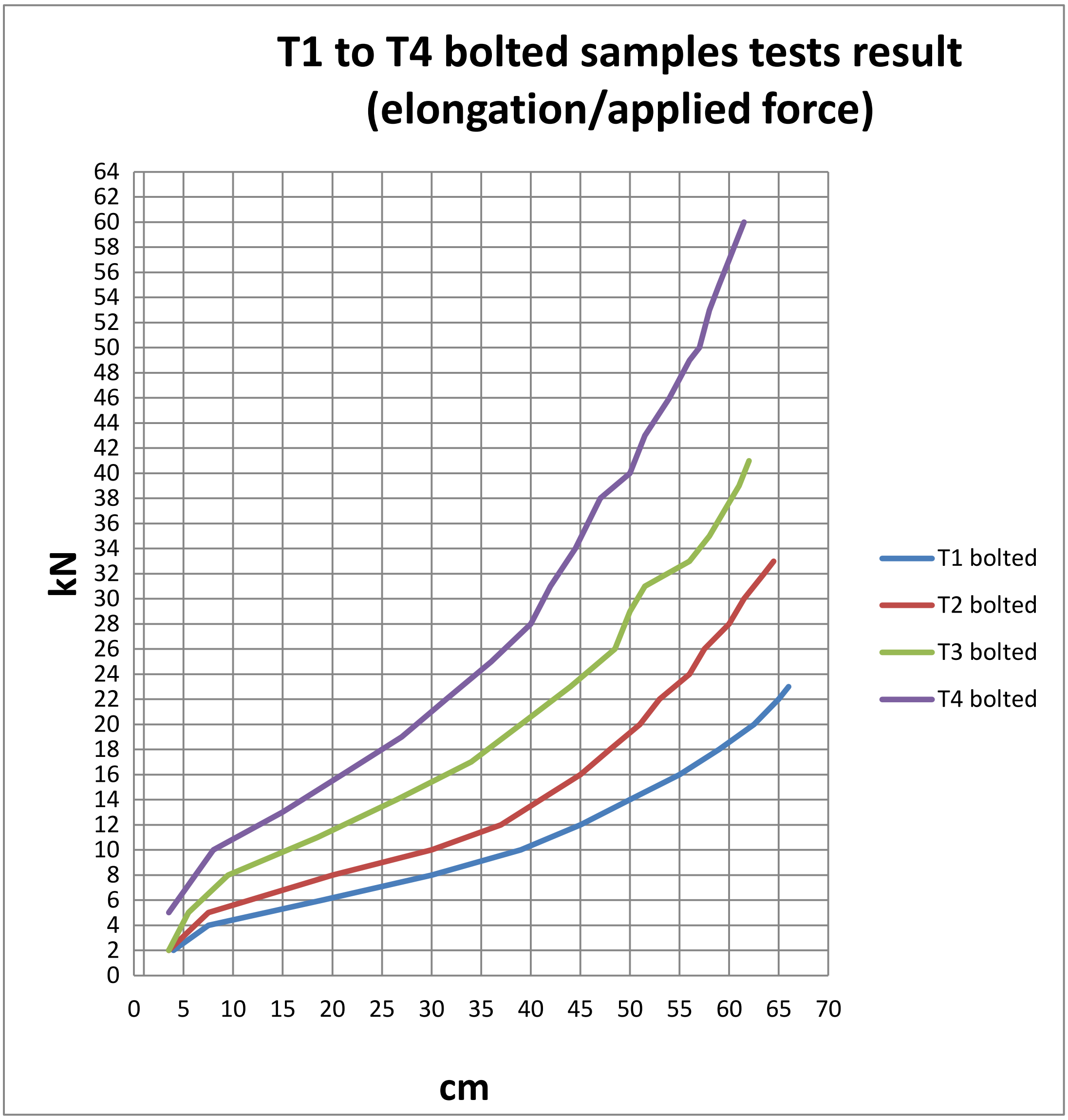
T1 bolted	
kN	cm
2	4
4	7,5
6	19
8	30
10	39
12	45
14	50
16	55
18	59
20	62,5
22	65
23	66

3.2 Setting the basic values of the 500 mm wide samples

As first set of tests where made the traction tests of the sole bolted 500 mm wide membrane strips of each type until the break point.

In this way it was possible to check the different working performances of each type.

It could also be confirmed if the break strength values given from the material ISO tests from the membrane manufacturer could be matched with this different testing machine.



Testing result chart 1

Beside analysing each membrane graphic value we have to focus to the known standard value that the membrane manufacturer gives to the end user following his ISO testing schemes.

With a good sense of personal relief the author could easily check the break point values in weft of the tests and it was given the following values:

T1 break point force: 23 kN/500 mm /10 = 2300 N/50 mm (in the ISO standard measure unit)

T2 break point force: 33 kN/500 mm /10= 3000 N/50 mm (in the ISO standard measure unit)

T3 break point force: 41 kN/500 mm /10= 4100 N/50 mm (in the ISO standard measure unit)

T4 break point force: 60 kN/500 mm/10 = 6000 N/50 mm (in the ISO standard measure unit)

If now consider that in the machine the testing samples are actually bolted with a loss of active working membrane width of around 20% (see the analysis of this matter at chapter n 2.3) we can multiply by 1,2 times the previous values to have the real stress resistance on a 50 mm wide active sample (and not on a 40 mm wide active one).

So proceeding in this way now we have the following results:

T1 break point force: 23 kN/500 mm/10 * 1,2 = 2760 N/50 mm very close to the 2900 N/50 mm standard value of that material type

T2 break point force: 33 kN/500 mm/10 *1,2 = 3960 N/50 mm very close to the 4000 N/50 mm standard value of that material type

T3 break point force: 41 kN/500 mm/10*1,2 = 4920 N/50 mm very close to the 5000 N/50 mm standard value of that material type

T4 break point force: 60 kN/500 mm/10*1,2= 7200 N/50 mm almost exactly equal to the 7200 N/50 mm standard value of that material type

After this first samples testing it was possible to proof that same result making a different test.

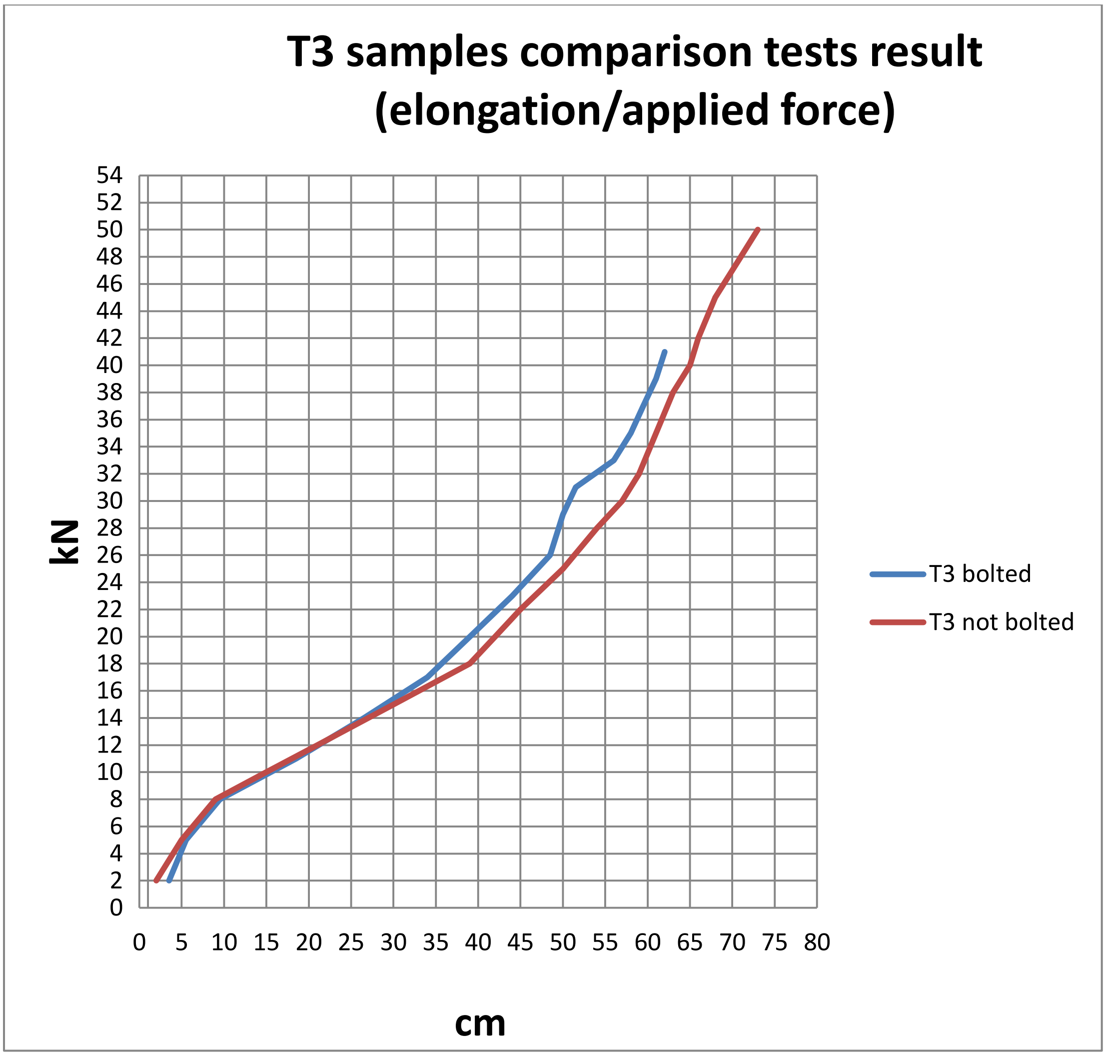
It was made a T3 sample of 500 mm width as the previously tested one but this time it wasn’t bolted to the traction flange punching holes in it.

Thanks to the high rigidity of the machine traction flanges it was possible to fix the testing T3 strip just screwing the bolts on both sides of the sample so that the full non punched width could be tested under breaking stress like the ISO tests made on the 50 mm strip.

With quite good precision the T3 sample broke exactly at the value of that material type : 5000 N/50 mm thus confirming that the relation between the bolted sample and the untouched fully working one is the following:

Breaking point value of the material type = 1,2 * tested value with the new big testing machine

See the following chart 2



Testing result chart 2

3.3 Setting the basic values of the 9 cm wide reinforcement strips

Proceeding in the same methodology of the 500 mm wide samples it was tested also all the possible combinations of reinforcement 9 cm wide strips that where then be welded on the different types samples.

The complete set of reinforcement strip is the following:

9 cm T2 strip

9+9 cm T2 strips

9 cm T3 strip

9+9 cm T3 strips

9 cm T4 strip

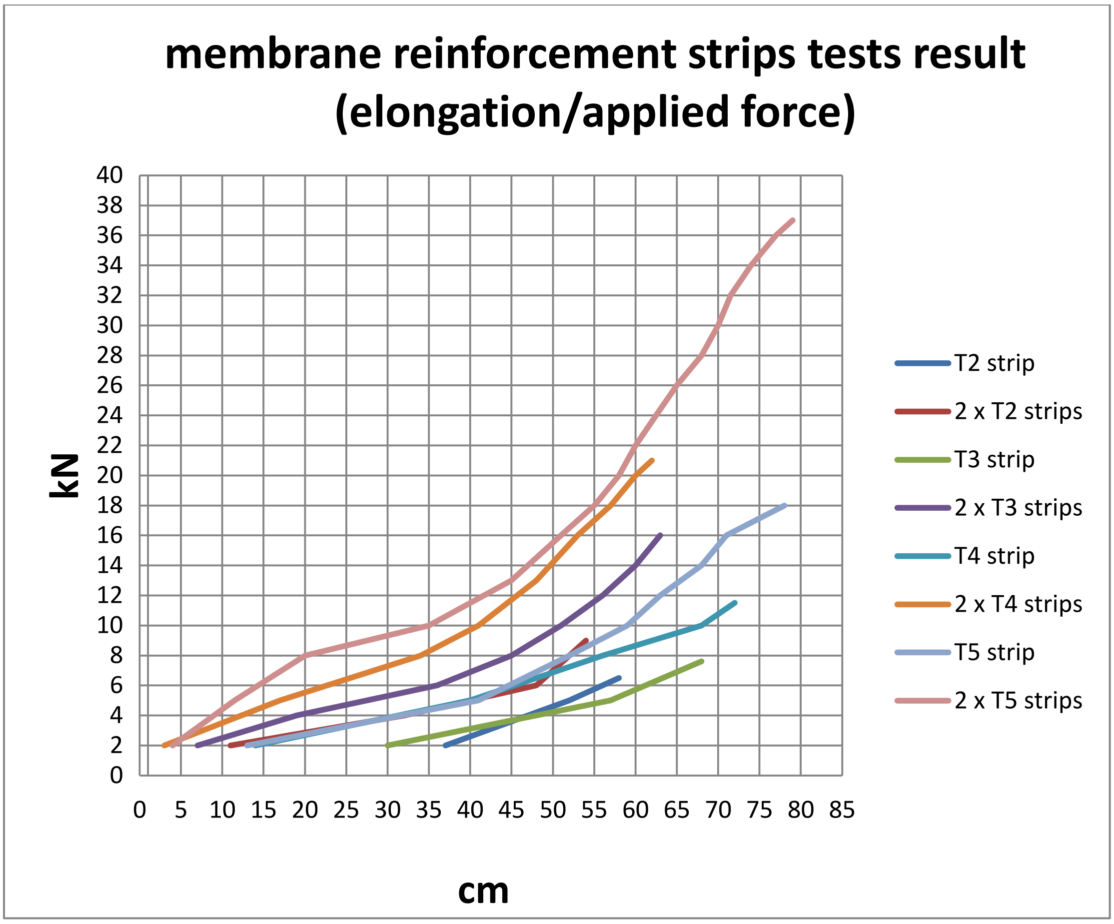
9+9 cm T4 strip

9 cm T5 strip

9+9 cm T5 strips

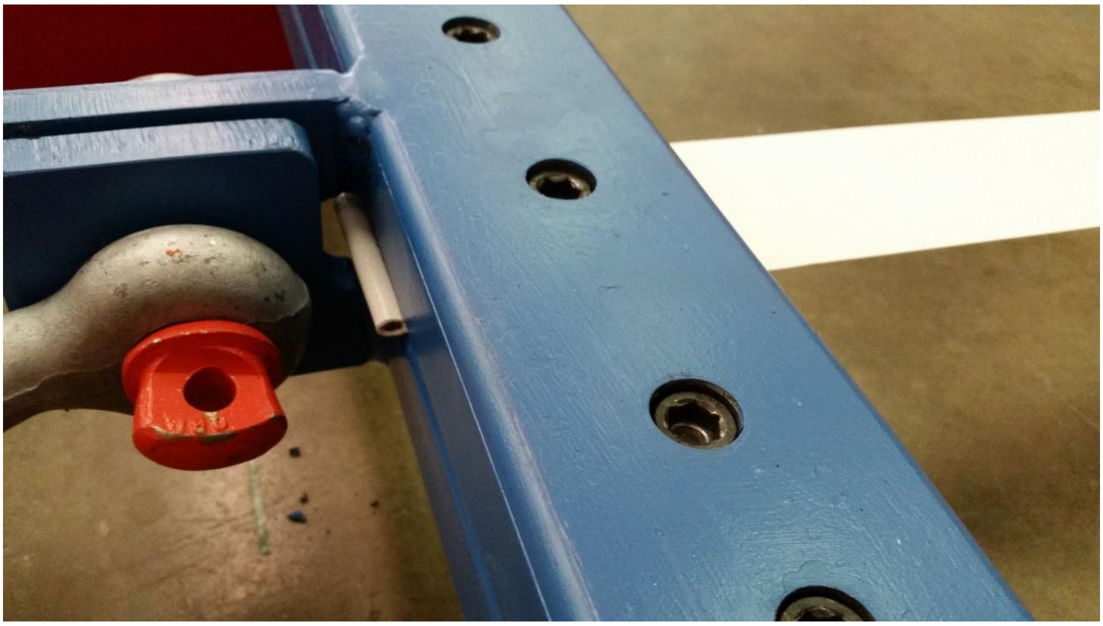
It was chosen to select specific types of reinforcement differently on each support membrane type sample. For example it could not be used a type 5 reinforcement strip on a type 1 membrane support due to the fact that the type 5 is very difficult to weld on a thin type 1 with the risk of burning the T1 while the T5 is still cold.

Here under in chart 3 is the complete set of tests made on the previous combination of strips.



Testing result chart 3

It has to be clarified that for all the tests of the reinforcement trips, either in the preliminary tests here above and during the tests on the 500 mm samples, the strips have been fixed under the flange with the keder ending but without the need of a bolt in the section. This have been possible because the tested strips have been placed in the centre of the steel flange where the bolts are symmetrically spaced by 100 mm so the bolts have been kept outside the strips by few mm, as it can be seen in picture hereunder. This caused obviously the full performance work of the strip material having been free from punched holes needed for the insertion of the bolts of the flange.

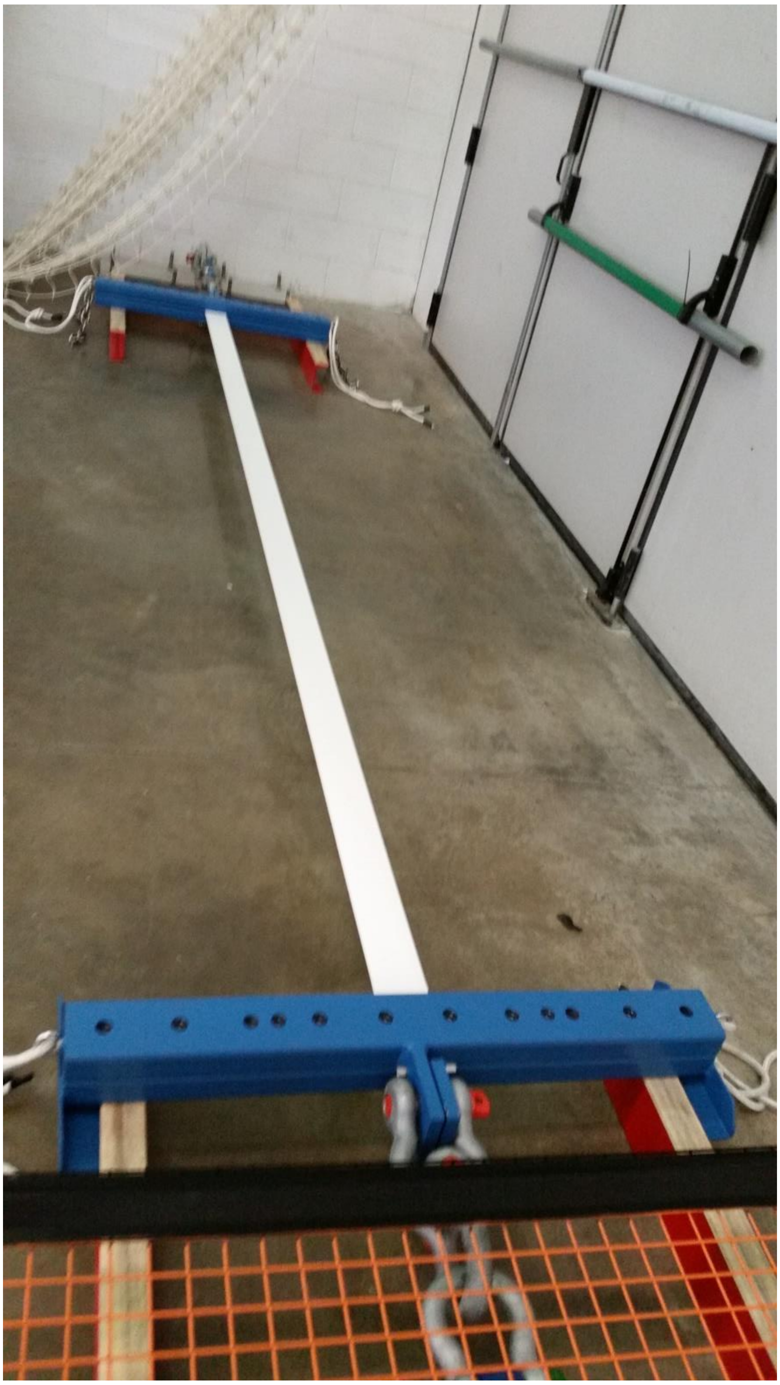


Picture 14. View of the reinforcement strip anchoring scheme where on the outside left of the flange the Keder rope profile is showed and the testing sample is fixed between two central bolts without the need of a punching.

This testing choice have been chosen by the consideration that in the real cases it is almost possible to select the areas of a bolted flange where are known the location of the bolt pattern. So it is quite easy to produce a cover with the reinforcement strips placed in a way to avoid to be punched under the anchorage flange.

So for the reason of the absence of weakening holes all the tested strips included the ones welded in double layers performed up to the breaking point of their type of course proportionally relatively to the 90 mm width of the strips. It means that the double strip, with the exception of a weaker result from the tested T2, reached almost the double breaking point.

Also on the elongation side the results are coherent with the ones made with the unbolted version of the 500 mm wide samples meaning that there is no size scale effect on the uniaxial behaviour of the membrane if the membrane is kept free from bolting with punched holes.



Picture 15. View of a T3 reinforcement strip under stress

CHAPTER 4

TEST RESULTS

4.1 Testing the membrane in a progressive way

The testing have been made proceeding from the lighter membrane (the Type I) adding all the possible reinforcement belts and then moving up to the next membrane type up to the Type IV.

The Type V has been used only to make the reinforcement strips but not directly as a main membrane due to the fact that the Type V is very rarely used and produced by the main European membrane manufacturers and also the cost are much higher. So it made sense to limit the use of it only to the narrow belts reinforcement avoiding a widespread misuse of it.

4.2 Type 1 tests

In order to achieve the most valuable results in terms of enhanced resistance it has been chosen to execute the following tests:

50 cm width T1 alone

T1 with 9 cm T2 strip

T1 with 9 + 9 cm T2 strip

T1 with 9 cm T3 strip

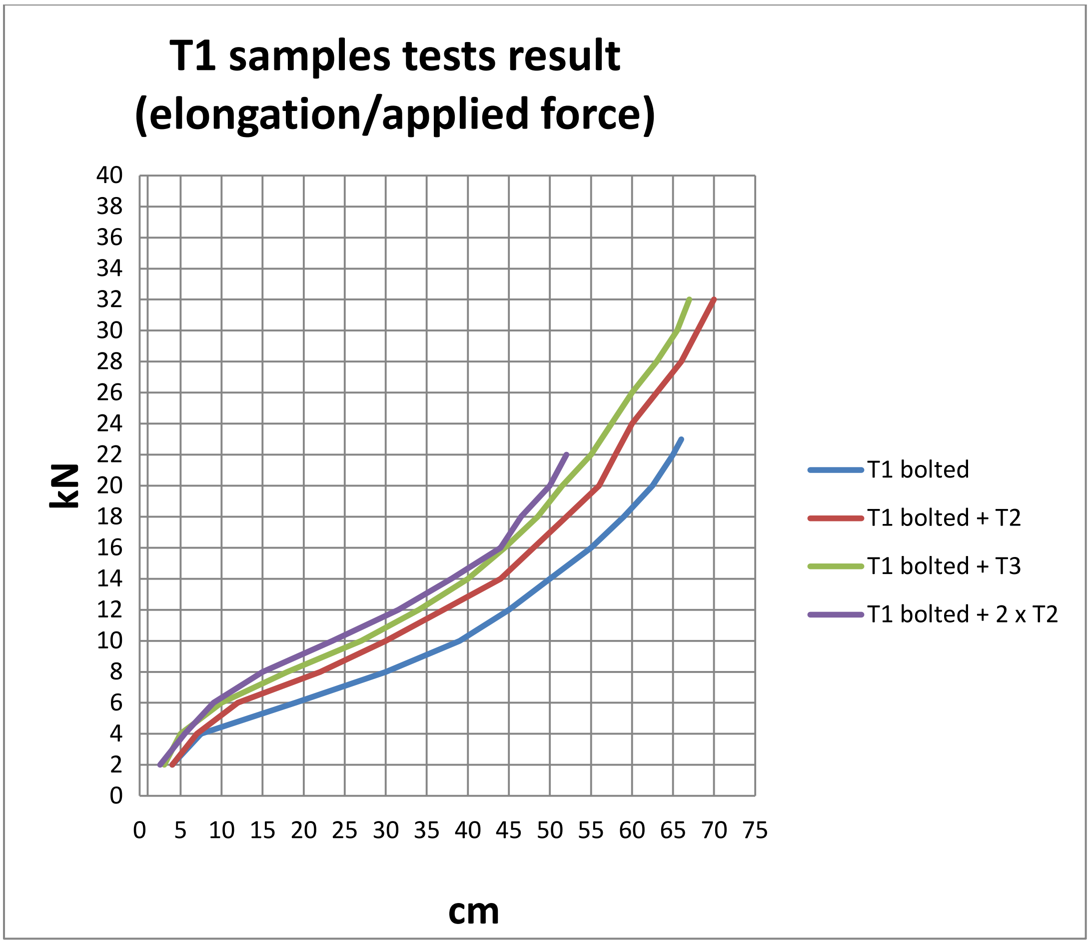
It wasn’t used to weld also a T4 or a T5 9 cm wide reinforcement strip on a T1 because it’s known that there is too much thickness difference between the T1 and the T4 and T5 in both polyester textile and in the PVC coatings.

This huge difference in material physical proprieties makes a High Frequency welding almost impossible due to the fact that during the welding process the thinner layer tends to be overheated while the thicker one is still cold and that prevents the perfect melting of the two PVC sides, greatly reducing the welding mechanical performance. There is also the chance that during the welding the lighter polyester fabric could be overcooked or even partially punched by the pressure of the welding electrode bar.

In fact the High Frequency welding is made under high pressure where for example typically a 1000 x 50 mm welding electrode is pushed with 10000 N force by pneumatic driven pistons to press the two overlapped membrane to achieve the best PVC layers adhesion.

During the high frequency welding process first the overlapped two membrane parts are pressed under the push of the cold electrode under the fore of the pistons.

After that few second time the High Frequency machine often automatically starts to heat the polar PVC molecules with an electric field of some KW power. Once the PVC is fused then the electric field is turned off and starts some time during which the welding starts to cool down still being pressed by the electrode. Finally the electrode welding bar is lifted up leaving the welding membrane ready for use.



Testing result chart 4

4.3 Type 1 tests evaluation

If we observe the chart 4 we can easily see the great increase of breaking strength resistance with the solution of welding the T2 or even a T3 9 cm wide strip over the T1. Both cases extend the breaking strength by a 50% factor. There is one case where adding a double layer of T2 belt weakens the system at the brake point even at a lower value than the single T1 membrane. The possible cause of the weakening of the double T2 reinforcement can be explained in two different ways that may act simultaneously.

The first weakening effect is caused by the High Frequency overheating effect of the thinner T1 layer respect to the two T2 thicker layers. This overheating reduces the resistance of the fibres of the polyester fabric that becomes more brittle.

The second weakening effect is given by the great difference in elasticity (and elongation) between the single T1 membrane that is more easy to stretch with a lower stress and the double T2 belt that has an higher elastic module. This great difference creates big shear forces just at the border between the belt welding and the single T1 material that cause the increase of the stress overall force in those little areas thus acting as a first spark for a cut of the fabric.

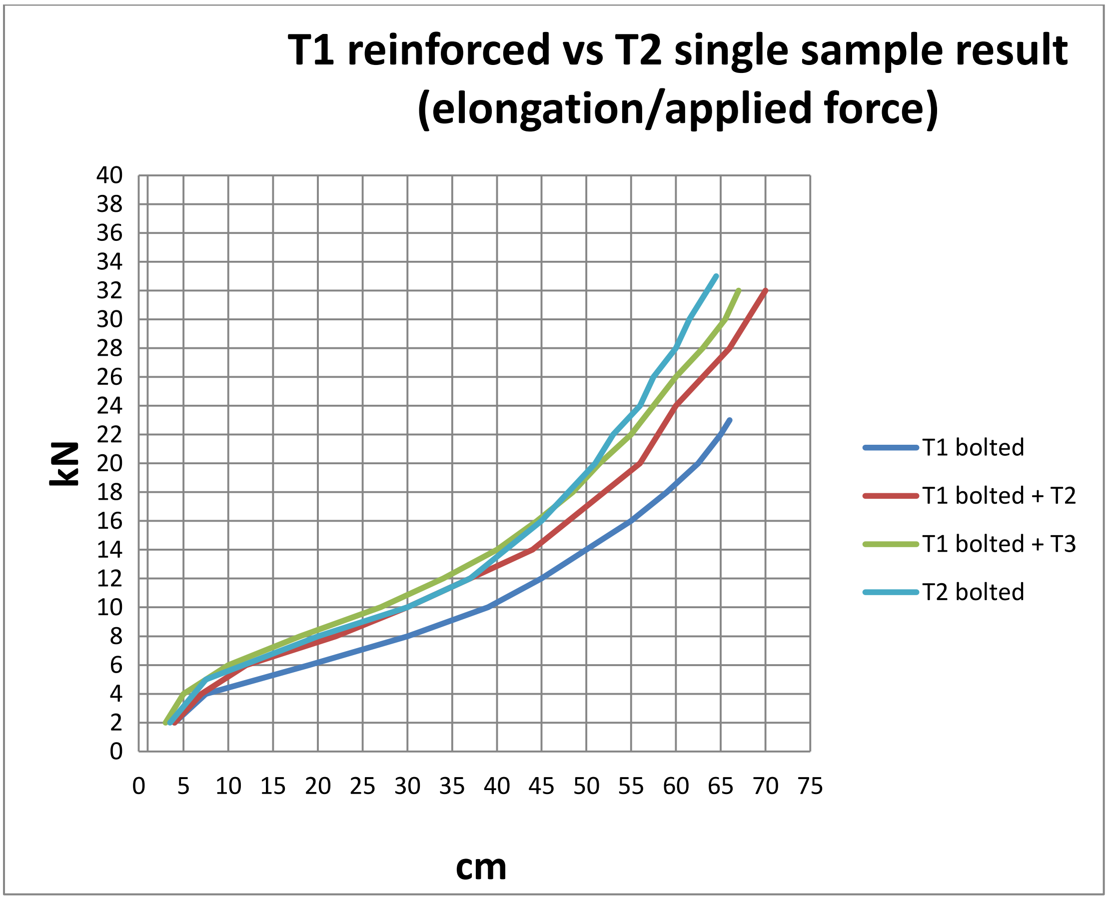
Now we focus on the lower left part of the curves of chart 4 where the stresses are within 2 and 10 kN. The normal working field of a membrane is considered by common international good building technique as a fifth of the break strength of the membrane due to many factors that reduce the theoretical resistance like fatigue, thermal action, welding errors, design imprecisions etc.…

Coming back to that lower left corner area of the chart 4 we can see that the effect of all the belts applied on the T1 membrane is to cut in half the elongation under the same stress. In numbers we can see that at around 6 kN the elongation of the 500 mm wide and 4000 mm long T1 strip is 20 cm while with all the other reinforced samples the elongation reduces to only 10 cm.

This effect can be used to control the elongation of the T1 membrane without having too much to calculate compensation effects during the membrane cutting and welding process. The lower elongations is very useful in case there is to limit the sag curvature in the locations of a cover where there is more probability of ponding effect for rain or snow or even dust precipitations and accumulation.

4.4 Outcome of the research

Coherently with the scope of this Master Thesis the results of this testing on the T1 sample membrane give us the clear possibility of comparing the enhanced mechanical stress resistance and elastic module of the reinforced strips with a higher type membrane. In this case, as we can see in chart 5, the simple application of a strip of T2 over the T1 membrane increased the overall mechanical quality of the new form to reach the same characteristics of a complete T2 single membrane.



Testing result chart 5

As the chart 5 shows, the T2 bolted tested sample stays almost within the same elastic module of the samples with T2 and T3 reinforcement and only near the break point behaves more rigidly with less elongation.

4.5 Type 2 tests

In order to achieve the most valuable results in terms of enhanced resistance it was chosen to execute the following tests:

50 cm width T2 alone

T2 with 9+9 cm T2 strip

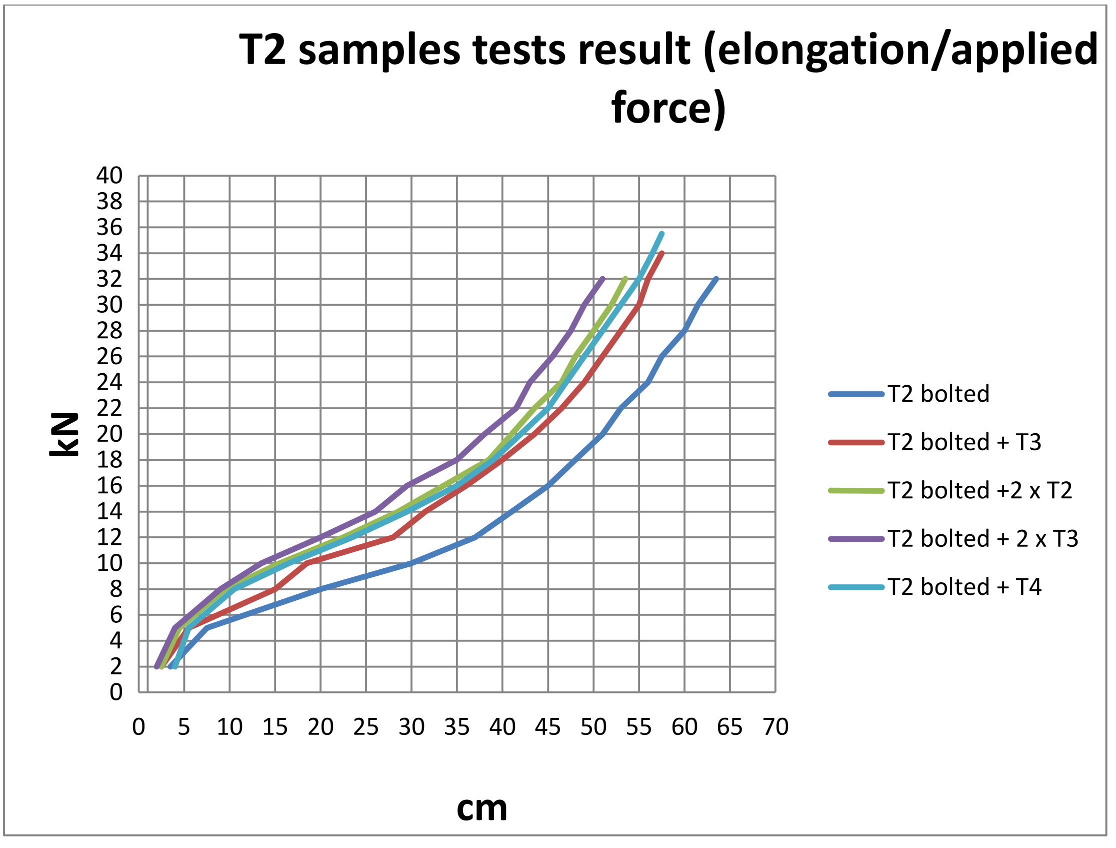
T2 with 9 cm T3 strip

T2 with 9+9 cm T3 strip

T2 with 9 cm T4 strip

We didn’t use to weld a T5 9 cm wide reinforcement strip on a T2 because there is too much thickness difference between the T1 and the T5 in both polyester textile and in the PVC coatings.

Also for the simple fact that a T5 is still too expensive respect with a T2 that there is less economical interest to make use of it instead of using an higher type membrane (as a T3).



Testing result chart 6

4.6 Type 2 tests evaluation

If we observe the chart 6 the results are very different respect to the ones made with the T1 samples.

In fact there are not solutions that gives the huge increase of breaking strength. However the samples made with the welding of a single T4 strip increase the break strength by a 10%.

In this case the big weakening effects of the double layers welding have not been seen due to the fact that already the T2 is strong enough to withstand higher welding temperatures overheating. Moreover the other weakening effect of the presence of the shear forces acted in a less striking way due to the close nature of the T2 respect to the T3 or T4 and thanks to the T2 polyester fibres higher tenacity compared with the T1 ones.

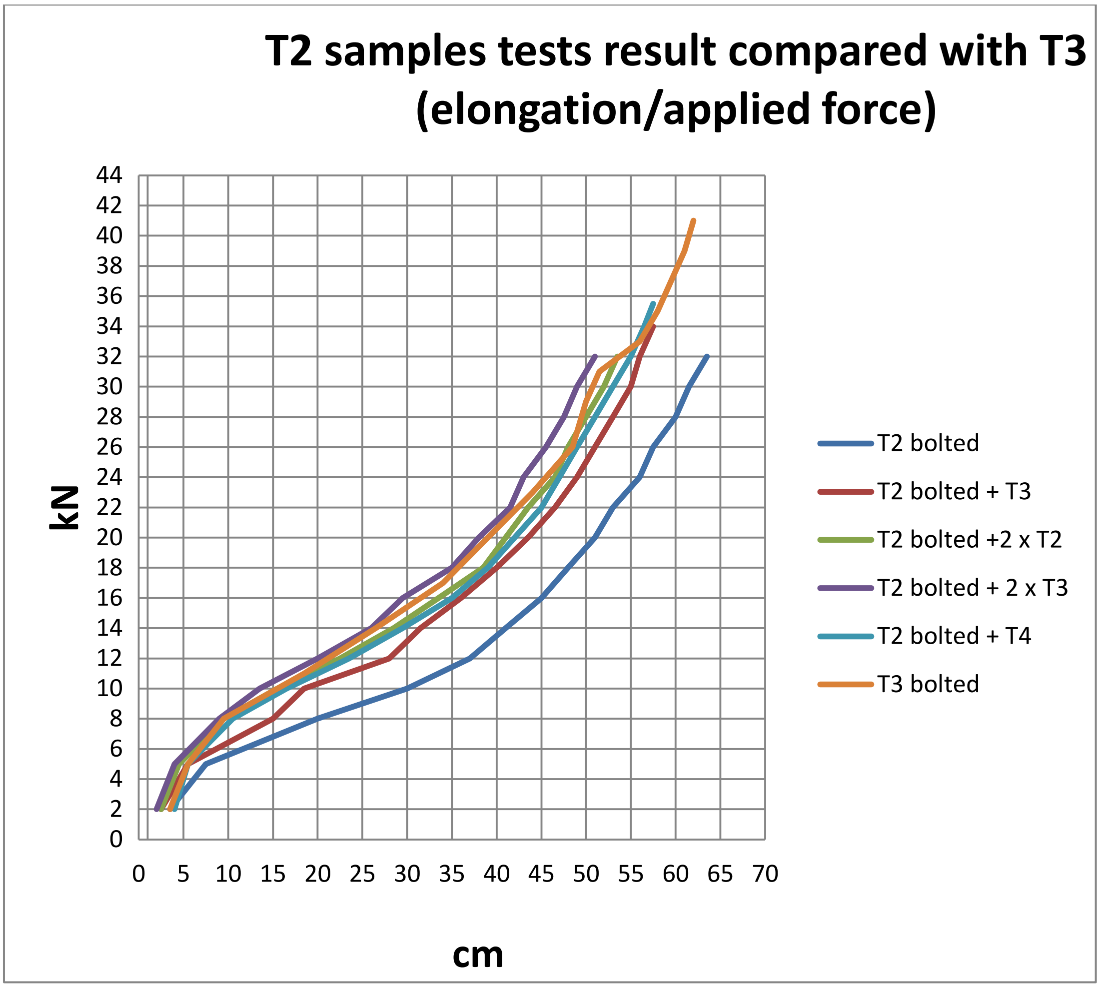
Now as in the previous analysis we focus on the lower left part of the curves of chart 6 where the stresses are within 2 and 10 kN that is the normal working stress field. The effect of the reinforcement strips is clearly visible in terms of elongation reduction.

Even more if compared with the T1 tests this effect is visible in chart 6 where at the lower stresses levels the elongation of the reinforced samples is only 35% of the ones of the T2 single membrane.

This effect clearly can be used to reinforce specific areas of big span tensioned T2 made covers where the need of keeping the shape fixed is compelling and also is necessary to increase the level of safety due to wind deformations or to potential ponding areas.

Economically it is equally interesting the solution of the use of a T4 or a T3 single reinforcement due to the fact that there are not big differences in mechanical effects. It is also interesting to use the double T2 reinforcement as the best economical solution to apply when there is not a big interest to increase the break strength of the material but when there is a need of containing the elongations of the material.

It’s quite simple to apply the double T2 reinforcement solution also for the fact that is the same material of the main cover and so there are no problems in purchasing the material and also to match the colour of the main cover.



Testing result chart 7

Picture 16. Complete view of a T2 sample with a T4 reinforced strip under high stress

4.7 Outcome of the research

In this case the results of the application of reinforcement membrane belts over the T2 did not impress us in terms of increase of the breaking strength, that anyway gave a 10% increase in resistance.

The solution of the double T2 strip reinforcement can be used cleverly to transform the elasticity behaviour of the T2 in a T3 like membrane as it can be checked in chart n 7.

One other interesting result it has been that there are multiple viable choices of reinforcement applicable to the T2 that can upgrade in the same way the stiffness of the membrane towards the T3 elasticity working field.

4.8 Type 3 tests

In order to achieve the most valuable results in terms of enhanced resistance it was chosen to execute the following tests:

50 cm width T3 alone

T3 with 9+9 T3 strips

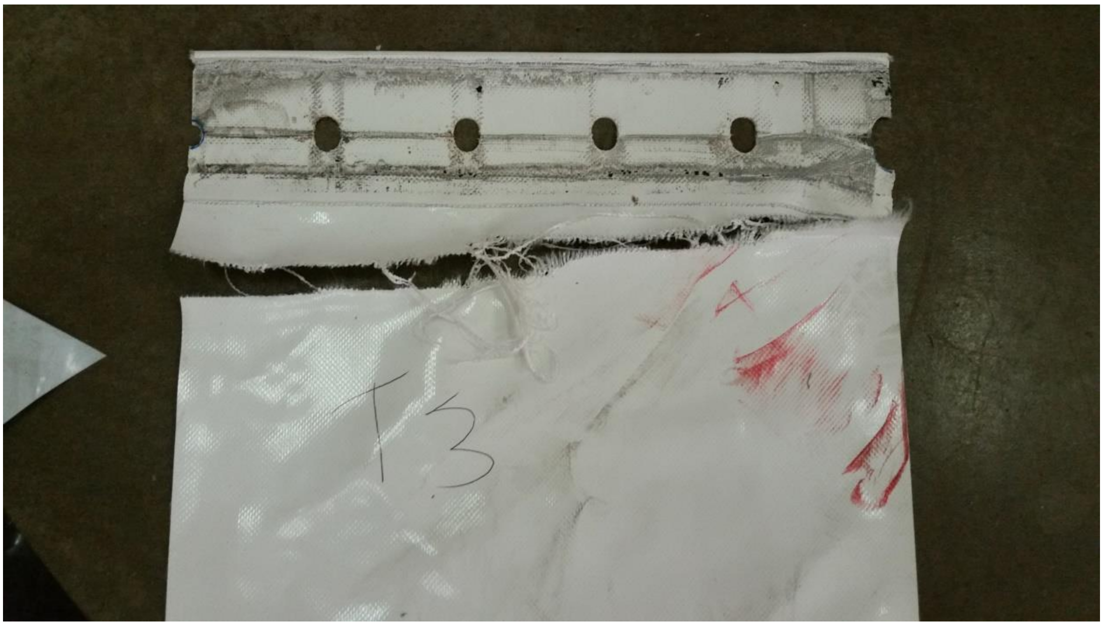
T3 with 9 cm T4 strip

T3 with 9 cm + 9 cm T4 strips

T3 with 9 cm T5 cm strip

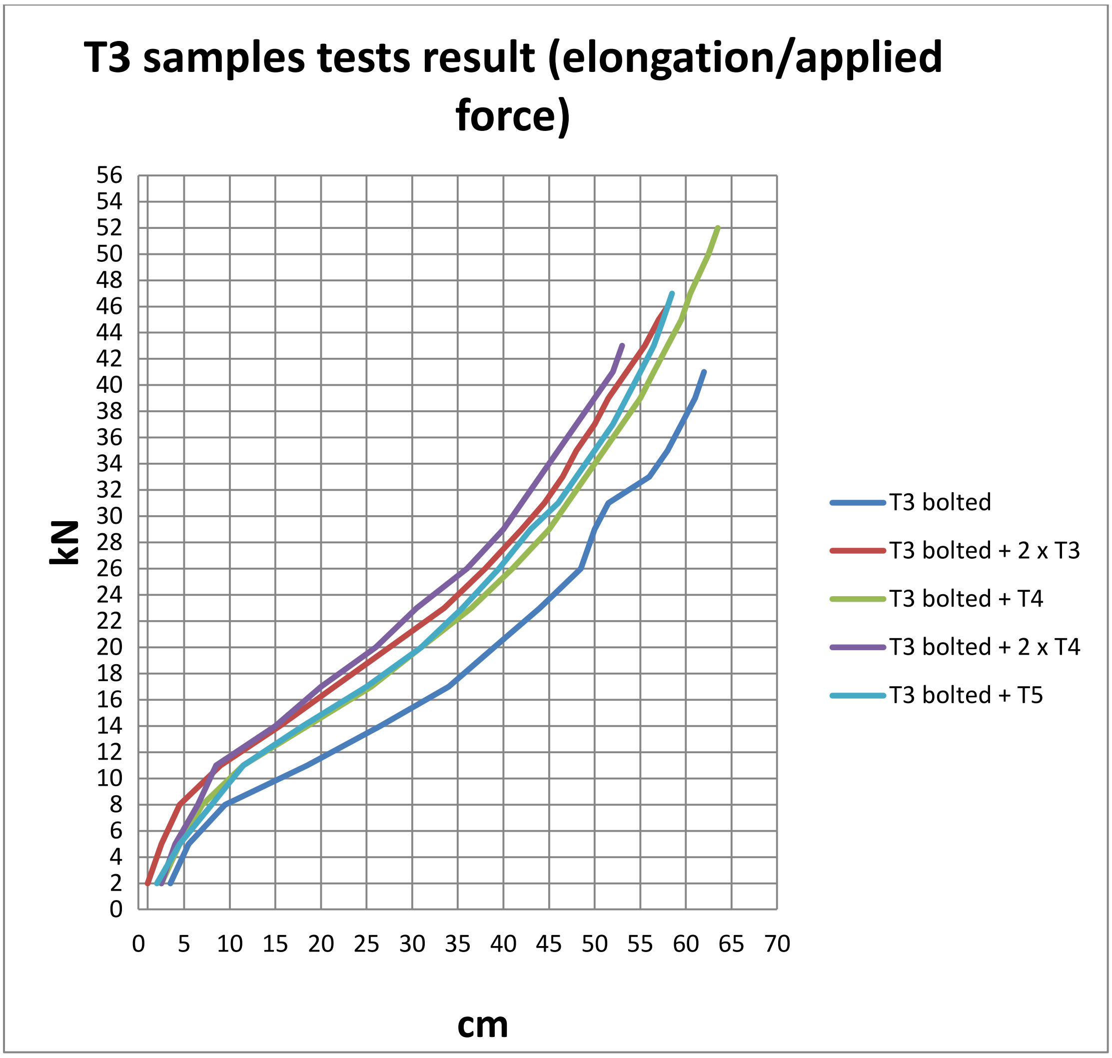
It wasn't welded a 2 x T5 9 cm wide reinforcement strip on a T3 because there is too much thickness difference between the T3 and the two T5 in both polyester textile and in the PVC coatings.

It was also feared that the high rigidity of the single T5 strip would be already too high if compared with the T3 behaviour in elongation thus creating too high shear forces that could reduce the stress resistance instead of enhancing it.



Picture 17. Broken single layer bolted T3 sample after the test

Note that the red coloured strips on the right side of the test where created by the sharp and fast contact between the flying broken sample and the red painted support steel railings thus demonstrating the huge elastic force released by the sample in a fraction of a second after the break.



Testing result chart 8

4.9 Type 3 tests evaluation

After the low gains in strength from the T2 tests here in chart 8 we can see again that the reinforcement strips causing a good increase of breaking point resistance.

One more time the sample with the reinforcement made with a single T4 strip has been the stronger solution with a gain of around 30% of the breaking point respect to the single T3 sample.

One interesting fact is that in the T3 tests for first it was used the T5 reinforcement strip that worked fine but still less successfully than the weaker T4 material. The possible explanation of this fact could be related to the closer nature of the T4 to the T3 in terms of elongation. For that reason the T4 didn't cause an high increase of the tangential or shear forces acting between the belt reinforcement and the main material.

The T5 strip is much more rigid or in other terms it shows a higher elastic module value than T4 and of course much more respect to the T3. That higher rigidity of the T5 reinforcement could then have created an earlier starting point for the break of the material.

In this case even more respect to the T2 tests the weakening effects of the double layers welding has been a less determinant factor due to the fact that already the T3 is strong enough to withstand higher welding temperatures overheating.

Moreover the other weakening effect of the shear forces presence acted in a less striking way due to the close nature of the T3 respect to the T4 or T5 and thanks to the T3 polyester fibres higher tenacity compared with the T2 and the T1 ones.

Now as in the previous analysis we focus on the lower left part of the curves of chart 8 where the stresses are within 2 and 10 kN that is the normal working stress field. The effect of the reinforcement strips is clearly visible in terms of elongation reduction even if less dramatically respect to the T2 material.

If we consider the elongation values of the different T3 samples at a traction force of around 8 kN we can see that the elongation of the majority of the reinforced samples is reduced by a 40% respect to the single T3 sample. If we look at higher stresses we can see that this difference is kept until the break point. In fact the curve of the T3 is running almost parallel on the right side respect to the group of the reinforced samples.

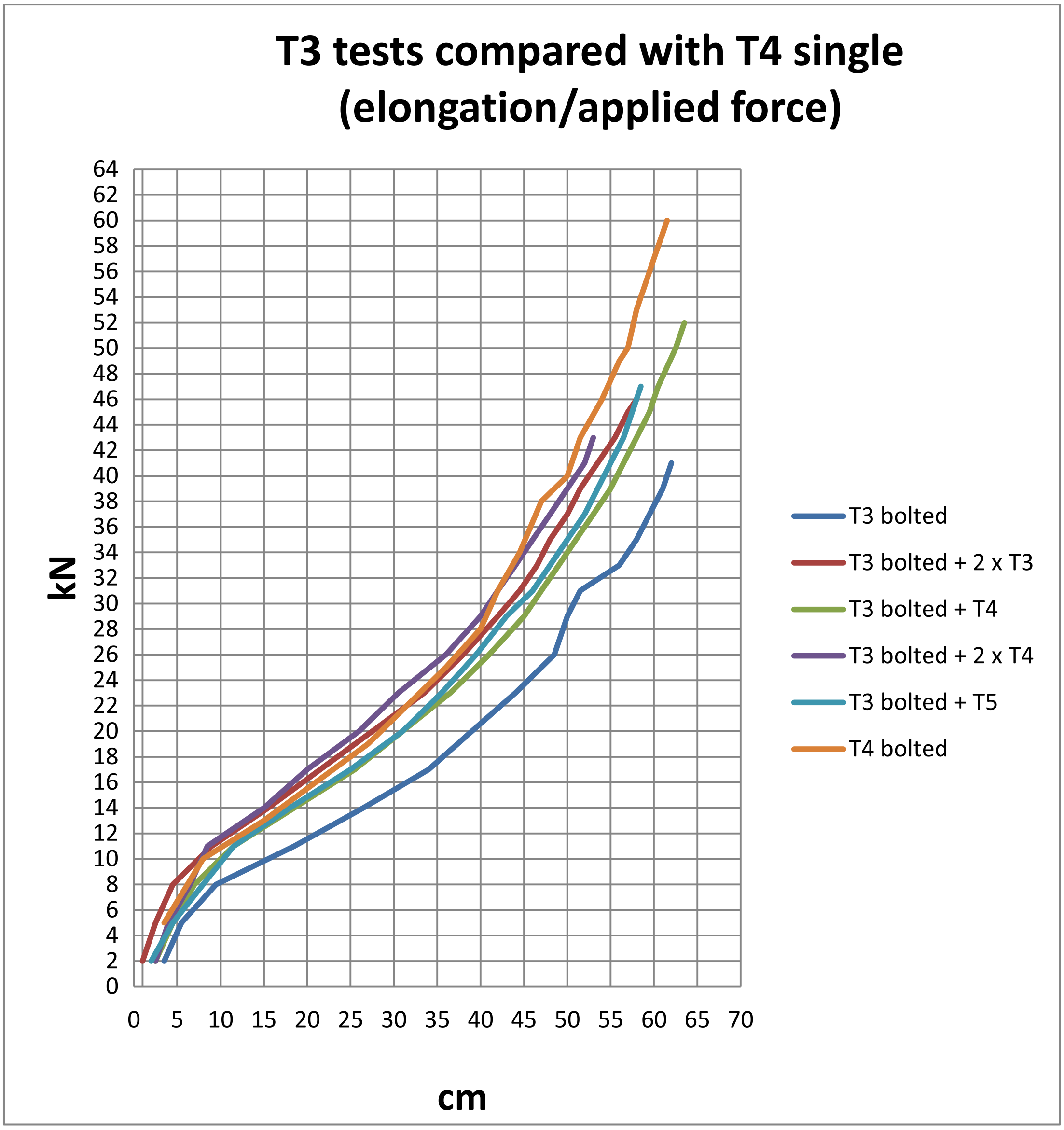
The acquired extra stability against the elongation of the samples with the reinforcement and in particular the ones with the double T3 layers of strip gives a practical solution to the design engineer of the membrane cutting pattern to choose when is needed an enhancement of control of the shape of the cover.

The solution with the T4, even if more expensive and problematic in terms of finding the right colour matching, is the one to use if, together with the need of increasing the stability of the form, there is also a need to increase the safe margin between the working stress and the max breaking point.

In this case the use of a T5 reinforcement is not recommended by the fact that it doesn’t increase the breaking point as the T4 strip does and also it is not the stiffer solution to control the shape as the double T3 does.

There is always to remember that the T5 is much more expensive than the T4 and much harder to find from any membrane supplier and it’s impossible to get it out for the shelf.

The double T4 reinforcement is also not a good solution if compared with the double T3 for both performance in the lower and in the upper stress field. The T3 reinforced in that way behaves more rigidly than all the other samples and most probably is the cause of the early failure of the breaking strength.



Testing result chart 9

4.10 Outcome of the research

The application of a T4 reinforcement strip gives to the T3 membrane a great improvement with a breaking strength increment upper limit of around 30%

Also there is a similar increase of the rigidity by a 40% in the first 15 kN tensile force and that characteristic is kept less elongated until the breaking point.

If we check carefully the chart 9 (and specially looking at the curves of the T3 bolted, T3 + T4 strip and T4 bolted) we can see that this new hybrid material behaves as a new intermediate form between a T 3 and a T4.

This new membrane type that could be called T3.5 is a good solution where the company that has to manufacture a membrane cover has a good working experience with the T3 membrane and it has mainly that quality on stock necessary to achieve higher safety standards in terms of breaking point and of lower elongation under loads. It is also a much cheaper solution if compared with the cost of a T4 full cover. Usually a T3 costs 40% less than a T4 membrane with the same quality refined textile and top coating.

Also one more advantage of this new solution is that the cover can be made much lighter than one using a T4, with a weight of around 1150-1200 gr/sqm against a 1350-1450 gr/sqm of the T4. It is also more easy to fold and to unfold than a T4 and to be packed in a smaller area with less cost of shipment and of installation. One more advantage is that is possible to weld together wider pieces of membrane with the same weight.

4.11 Type 4 tests

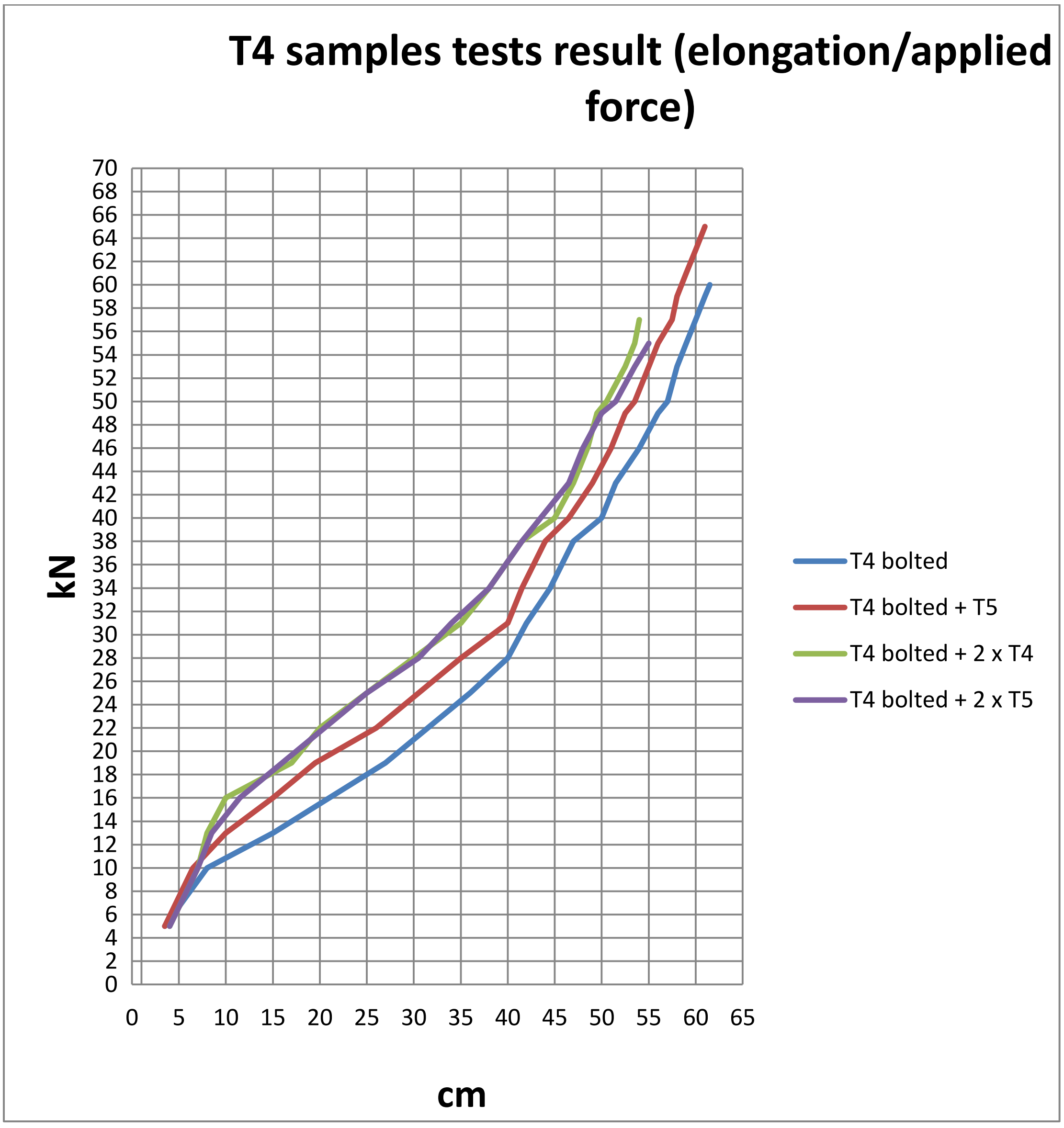
In order to achieve the most valuable results in terms of enhanced resistance it was chosen to execute the following tests:

50 cm width T4 alone

T4 + 9 cm + 9 cm T4 strips

T4 + 9 cm T5 strip

T4 + 9 cm + 9 cm T5 strip



Testing result chart 10

4.12 Type 4 tests evaluation

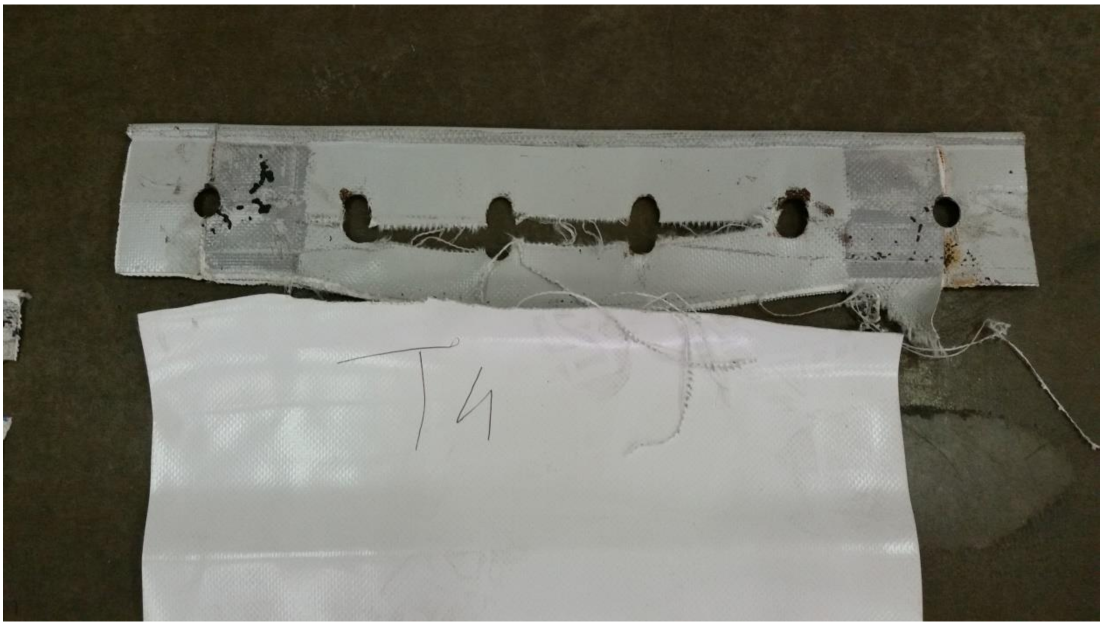
After the high gains in strength from the T3 tests here in chart 10 we can see again, like in the T2 samples cases, that the reinforcement strips cause only a relatively low gain in breaking point strength.

In this case, like the combination between the T3 and the T4 reinforcement close pair, the best performance achievement was made by using the close pair of upper type level: the T4 and the T5 reinforcement.

In fact he sample with the reinforcement made with a single T5 strip has been the stronger solution with a gain of around 10% of the breaking point respect to the single T4 sample.

What it has to be clarified in this last Type 4 testing round is that at the traction forces from 50 to 65 kN the test accuracy is less easy to achieve and control due to the fact that the steel anchoring flange of the testing machine could not create enough closing force to increase the grip of the membrane.

This effect possibly causes more direct work of the punched material against the closing 14 mm diameter bolts creating weak points with concentrated stresses where the membrane starts to be cut.



Picture 18. T4 single membrane broken with near welding lateral standard cut and breach in the line between the punched holes under the flange

With the use of more grip enhancement on the closing flanges it could be achieved also in the T4 case a better gain in traction resistance of the T4 + T5 strip combination respect to the T4 sole membrane with strength increments in percentage close to the ones of the T3 + T4 strip reinforcement respect to the single T3 membrane.

As it is clear from the chart 10 results the use of double reinforcing strips of T4 or T5 is negative for the breaking point elevation. In fact both solutions reduce the resistance of the T4 material below the single T4 working stress field.

For sure it has to be eliminated the effect of the welding of 3 big layers like T4 or T5 together because for the welding experience it was deliberately decided to weld them together using a more long welding time and less energy so that the materials could be welded properly without having to be overheated.

What made some difference is that in order to close together the samples with such a thicker reinforcement in the centre of the 500 mm wide strip it was inserted one extra layer of the same T4 or T5 reinforcement strip under the anchorage flange on both sides of the reinforcement strip. Without that mechanical trick there was an evident slippage of the T4 main membrane on both sides of the reinforcement double T4 or double T5 strip due to the fact that the flange could not press sufficiently hard the T4 membrane close to the much thicker reinforcement strip.

Still even using that solution was a partial success because the increase of multiple layers of non-welded membrane under the flange caused some increment of slippage that is the probable cause of the earlier than thought break of the tested samples.

Now as in the previous analysis we focus on the lower left part of the curves of chart 10 where the stresses are within 5 and 15 kN that is the normal working stress field. The effect of the reinforcement strips is clearly visible in terms of elongation reduction in a similar percentage of the T3 tested samples.

If we consider the elongation values of the different T4 samples at a traction force of around 10 kN (over 50 cm wide sample) we can see that the elongation of the single T5 reinforced sample is reduced by a 30% respect to the single T4 sample.

If we look at the samples with the double T4 and T5 strip the reduction of elongation increases up to a 60%. In fact the curve of the T4 is running almost parallel in the chart n 10 on the right side respect to the group of the reinforced samples.

The acquired extra stability against the elongation of the samples with the reinforcement and in particular the ones with the double T4 layers of strip gives a practical and economical solution to the design engineer of the membrane cutting pattern to choose when is needed an enhancement of control of the shape of the cover.

The solution with the double T5 is not recommended due to the fact that it doesn’t do any better respect to the double T4 strip and it cost much more.

4.13 Outcome of the research

The application of a T5 reinforcement strip gives to the T4 membrane an apparently slight improvement with a breaking strength increment upper limit of around 10%. As written in the previous page such strength enhancement could be incremented by the use of specifically designed anchoring flanges that can increase both adhesion trough compression force and also keep pressed evenly membrane with different thickness endings where the reinforcement strip passes in the flange.

In that future scenario the gain of breaking strength of a T4 that already is commonly used for high stressed covers and in high end market application could be easily applied to increase the safety required level under the ever increasing limits imposed by the international rules for the calculation of the wind resistance of such structures.

What is a fast upgradable application of this test result is to use the double T4 strips to really “fix” the membrane elongation within very small amounts with working stresses not higher than 10 kN over half meter.

4.14 Analysis of a mechanical behaviour of a one side not restrained reinforcement belt

In all the previous tests made with the 500 mm wide samples reinforced with the single or double 9 cm strip, the strips where carefully fixed on both sides to the anchoring steel flanges trough the keder endings.

In order to see what are the mechanical effects in case of letting one side of the reinforcement strip ending in the membrane without being anchored to a fixed edge like the testing machine flange.

In the following draft testing figure 8 it is showed how the look of the reinforcement strip was planned, seen on the free end still totally welded to the lower membrane.

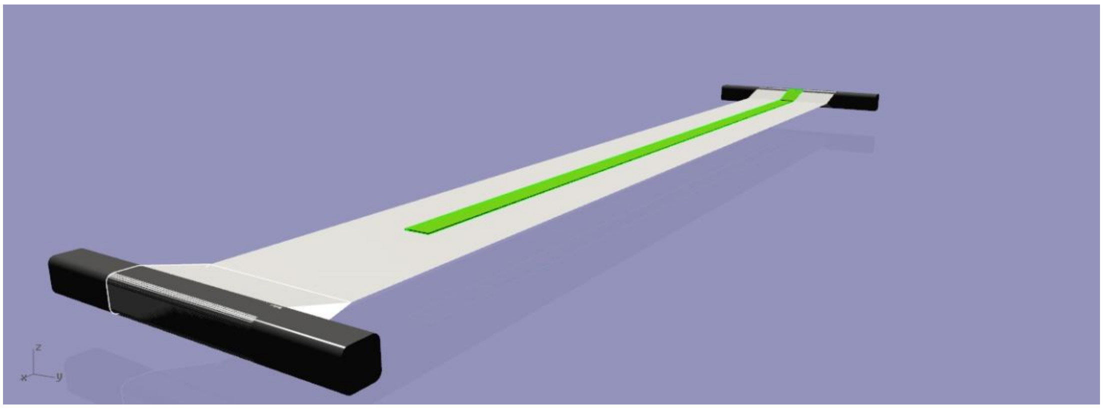


Figure 8. Here can be seen schematically how this test was planned. The green colored strip is the reinforcement that is welded on the T2 sample and it's anchored only on one side.

The figure 8 was made before the construction of the testing machine and reflects roughly the same geometrical conditions that after where applied in the real test.

The test geometry is the following: the sample membrane is a T2 with the standard tested width of 500 mm and length of 4000 mm. The special one side fixed reinforcement single T4 strip is 3000 long thus ending on one side at 1000 mm from the steel flange where the sample underneath is fixed as usual. From the theory it was expected to see some reduction of strength due to the action of big shear tangential stresses acting on the side ends of the free side strip.

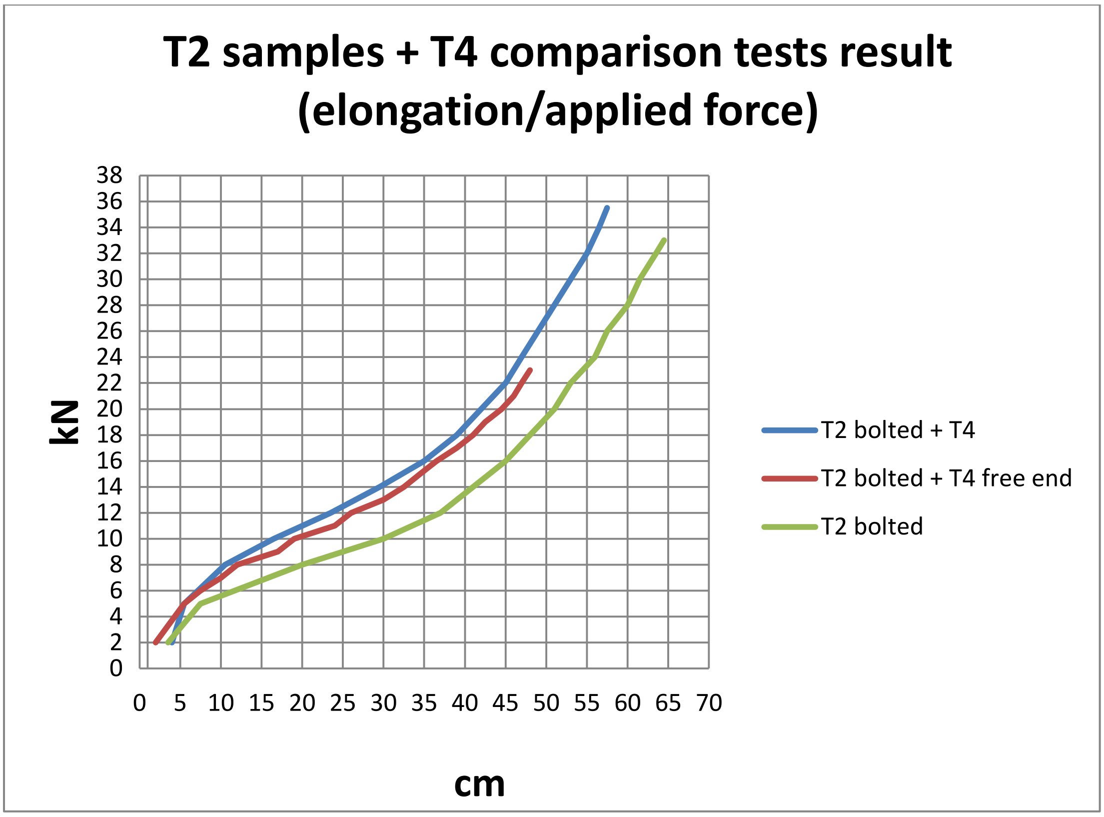
This effect caused the premature rupture of many samples in the previous tests, where the extreme stiffness difference values between the membrane sample and the double reinforced strip, like 2 x T3 or 2 x T4 or 2 x T5, created great tangential shear stresses. But, where in the other tests the shear forces where only to be deducted indirectly, here the scope of this specific test was to visually see some effects even before the early rupture of the sample.

Picture 19. Complete view of the sample under test

4.15 Test evaluation on the effects of the strip's missing anchorage end

Before checking the visual effects of the mechanical stress anisotropy between the two materials at the membrane reinforcement end we can first analyse the stress chart result of this test.

It is useful to compare it with the previously made test of a T2 reinforced material with a single T4 strip like the one tested now but with both ends anchored.



Testing result chart 11

If we look at all the curve chart 11 it is easy to see that the new testing sample did perform much more weakly respect even to the single T2 membrane.

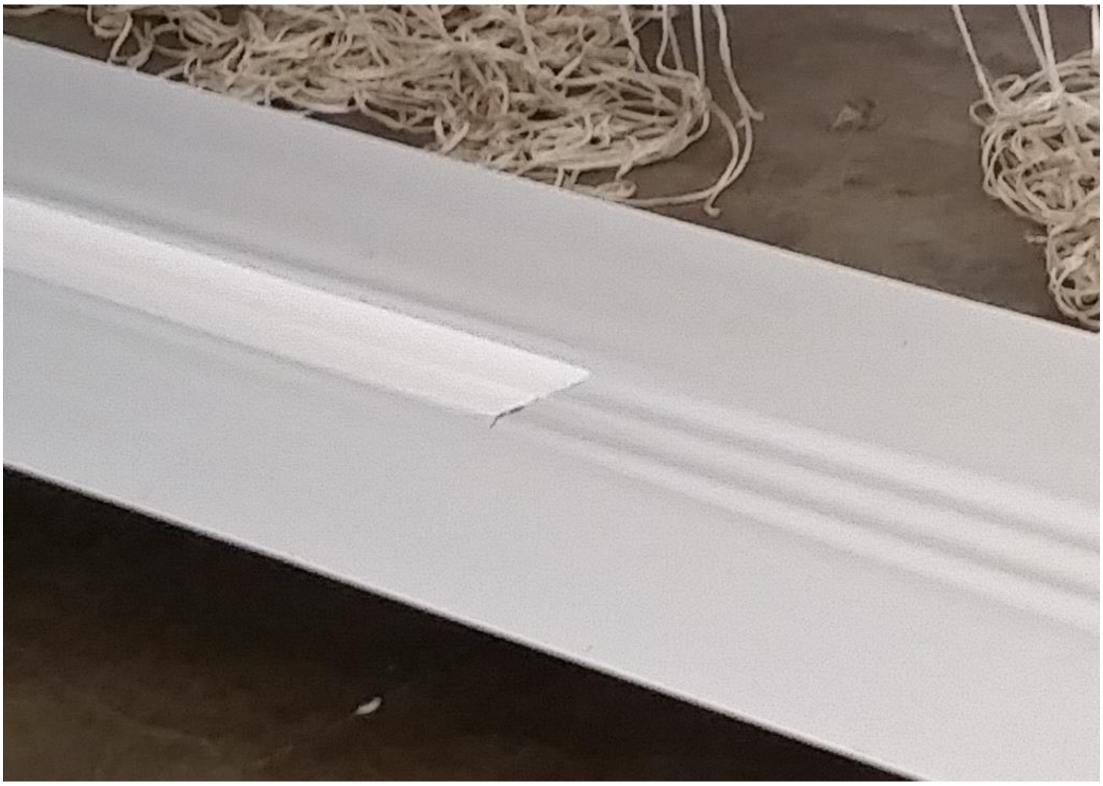
The weakness effect made by the adding of the welded free end reinforcement strip reduced the breaking stress force by a 33%.

It is also to take note that, even if the reinforcement strip ended 1 m before the sample length meaning that the sample main T2 membrane was working alone in the last one meter of the sample, the tested system did almost behave like the sample with the T2 + T4 both end anchored strip. The lines with blue and brown colour run almost closely parallel for all the length of the brown one.

The stiffness of both lines is quite higher than the one of the single T2 membrane. This quite surprising behaviour means that there must have been a rigidity effect made by the 3 m reinforced strip that reduced the natural elongation of the T2 even in the last 1 m where the strip as not present.

This assumption comes from the fact that the T4 strip being ¾ of the length of the T2 sample should in theory have caused a stiffening effect equal to the ¾ of the sample with the T4 reinforcement strip anchored on both ends.

In reality there must be some other mechanical effects that cause that extra 1/4th missing stiffening effect and that is given from the differential elongation of the two materials.



Picture 20. Enlarged view of the strip welded end under stress

When we look on the tensioned sample free end as in picture 20 we can see that there are some kind of wrinkles that run parallel to the strip and eventually enlarging on the sides when they go far from that edge.

Thanks to the new testing machine it is easy to see the big visual effect of the restraining action of the strip even to the T2 on its sides. The main sample material is pulled backwards by the T4 restraining welded strip thus creating big shear deformations that pulled the membrane also from the side letting work also the weft.

The oblique pulling effect can be seen from the 3 dimensional displacement of the material in wrinkles that concentrate more T2 material to compensate the lack of the T4 missing reinforcement strip.

The shear deformation induced by the big elongation difference in warp let work the T2 membrane more like a biaxial mode with the weft polyester fabric contributing to discharge sideways the extra local stresses.

If this shear contribution would not be there, than the sample would have been deformed only as a sum of 3 meters of a reinforced T2 material + 1 m of non-reinforced T2.

So the test demonstrated that unequivocally the shear stresses can act as stress discharger where a local concentrated differential stress is active.

It could be also demonstrated that making reinforcement free ends with an enlarged and diagonal end as showed in the figure 9 it could be elevated the breaking point of the still weak system increasing the work of the shear forces to take out a bigger part of the local extra stresses.

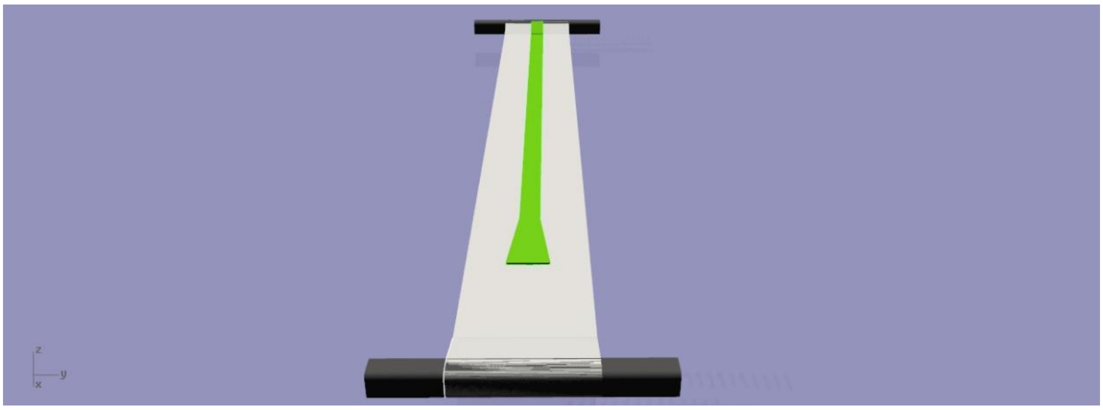


Figure 9. Draft view of sample with enlarged free welded end.

Obviously the test also demonstrated that there must be a big attention in the need of carefully anchoring both ends of any kind of reinforcement specially when the latter is welded to the main membrane.

Picture 21. Broken sample of T2 with one end free welded T4

CHAPTER 5

GEOMETRIC AND MECHANICAL ASPECTS OF MEMBRANE REINFORCEMENT

5.1 Introduction

After having researched the strength performances of reinforcement strips now the following consequent step is to define the best method to choose the correct placement of the reinforcements over a tensile membrane of any given shape.

To allow the full understanding of the ways the stresses and the geometry of a given shape interact it is important to set a necessary number of statements defining the geometrical and mechanical basic principles of this specific method. [8]

First Geometric Statement

Through every point of a surface there is a bundle of geodesic lines. In every direction from this point we have one geodesic line. This is true for surfaces with negative Gaussian curvature and for such with positive Gaussian curvature.

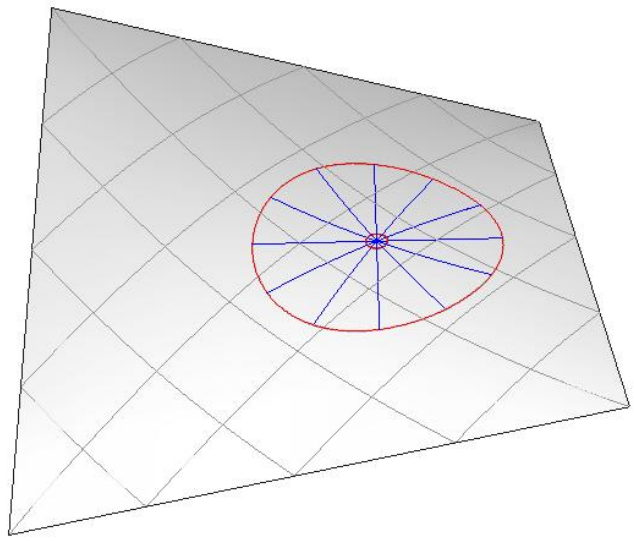


Figure 10. Example of bundle of Geodesics trough one point on a surface with negative Gaussian curvature

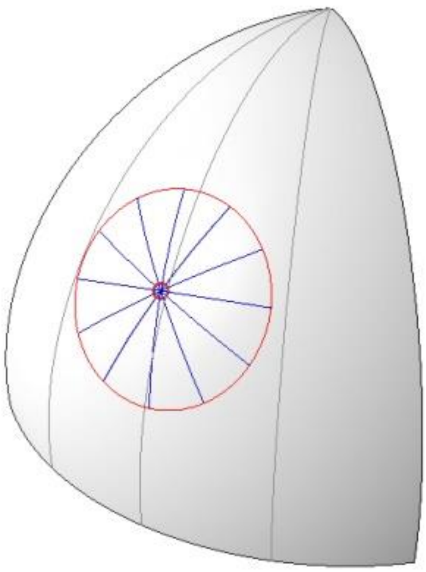


Figure 11. Example of bundle of Geodesics trough one point on a surface with positive Gaussian curvature

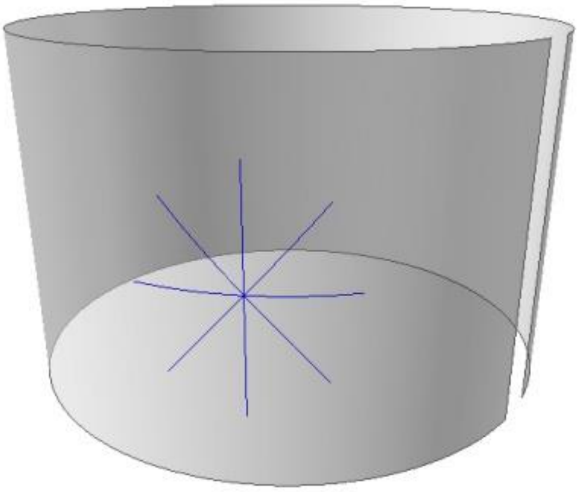


Figure 12. Example of bundle of Geodesics trough one point on a surface with zero Gaussian curvature

Second Geometric Statement

The developed view of a geodesic line on a curved surface into a flat surface is a straight line.

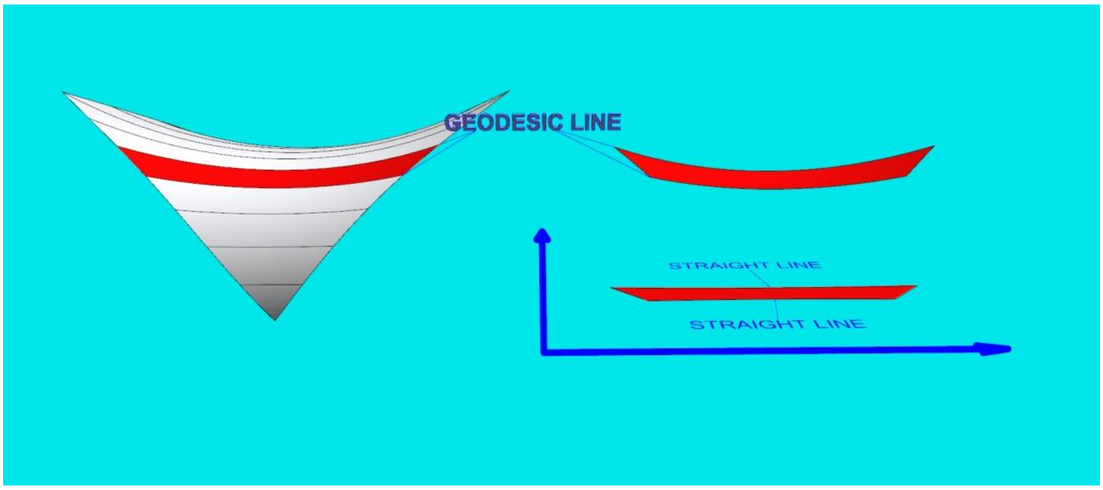


Figure 13. Example of strip selection over a hyper shape with geodesic lines and the flattening effect on a two dimension plane that shows the two geodesic sides as straight lines.

Third Geometric Statement

Through every point of a surface we have at minimum two directions of mean curvature. The two directions are perpendicular. All these directions define a system of two lines, the lines of mean curvature. Lines of mean curvature are not geodesic lines, but they are in special cases not so different.

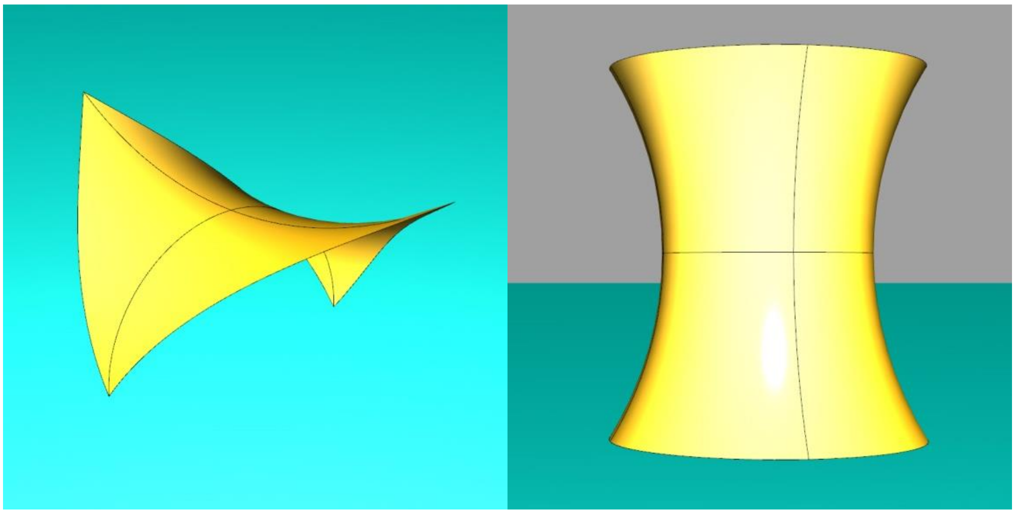


Figure 14. Examples of mean curvature lines on two shapes

5.2 Geometrical method to define the optimal location of the reinforcement strips

The most functional and mathematically determined way to choose the direction is to seek to keep the reinforcement strip straight in order to let it work in a direction parallel to the mean stresses on the surface.

For a different but not less practical reason it's very useful to have straight strips cut parallel to warp or weft from a membrane roll because than the scraps will be zero, thus eliminating a source of extra costs. Thus the welding can be done with High Frequency using standard straight electrode bars.

So we have to search to find a way to determine paths on a double curved membrane that once flattened on a 2 dimensional "table" become straight. The reinforcement strip then can be welded to the membrane in the direction of a geodesic line. The best choice for the geodesic line out of the bundle will be parallel to one of the two lines of mean curvature.

The process of choice then will be:

1. Choose a line of mean curvature, preferred one which goes somehow through the middle of the membrane.

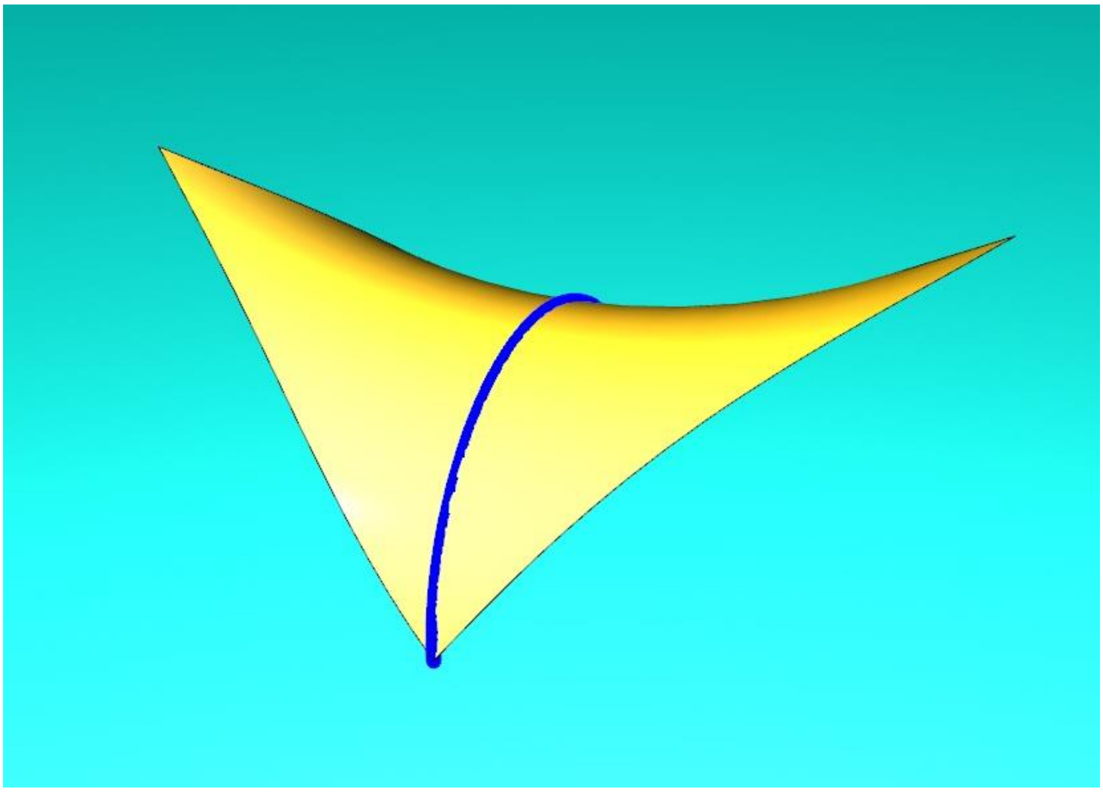


Figure 15. Mean curvature line in the centre of the shape

2. Choose a geodesic line through the middle point of the line of mean curvature with the orientation perpendicular the line of mean curvature. The direction of this geodesic line at the chosen point is the direction of the second mean curvature because of the Third Geometric Statement.
3. Thus the reinforcement strip will be approximately parallel to the second mean curvature at minimum in the surrounding of the first line of curvature. This orientation will help most in taking over the load by the welded strip.

The 3 steps method defines the correct surface paths, that can be mathematically determined under the geometrical statements, assures the use of the minimum amount needed of welding reinforcement straight strips, placing them in the best location to increase the stress resistance of the cover without compromising is own stability with the adding of unbalanced stresses.

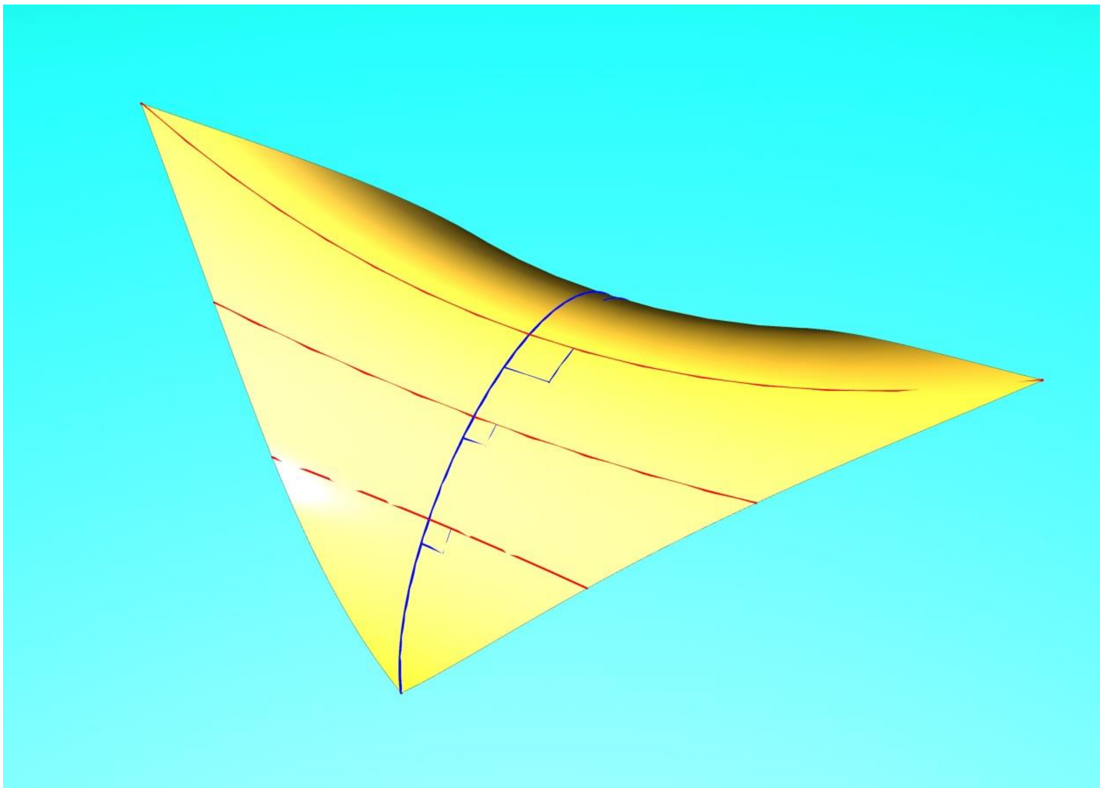


Figure 16. Steps 2 and 3 of the method

If the point n° 3 is not fulfilled there could be cases as in the figure 17 where without following the direction perpendicular to the mean curvature it is possible to choose the geodesic lines directed in a single tilted pattern that if used to reinforce the cover would create a torsional effect that could surely compromise the shape stability.

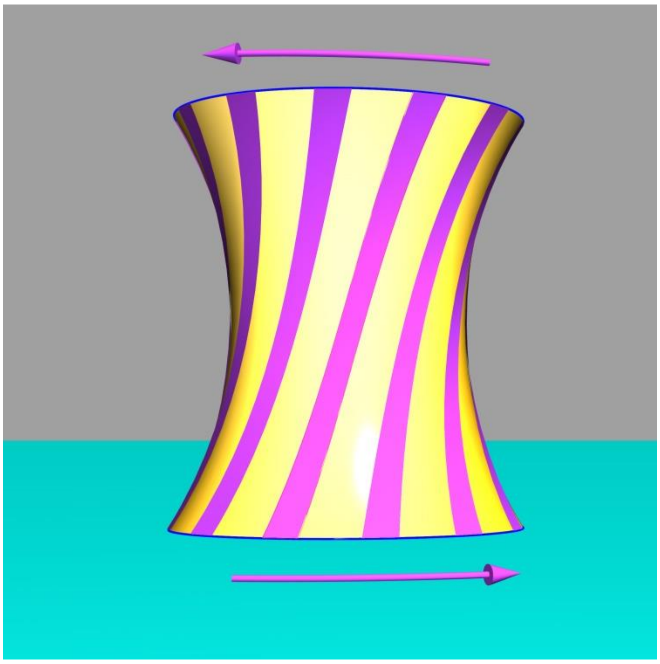


Figure 17. View of the torsion effect of wrongly applied reinforcements on geodesic lines not directed perpendicularly to the mean curvature

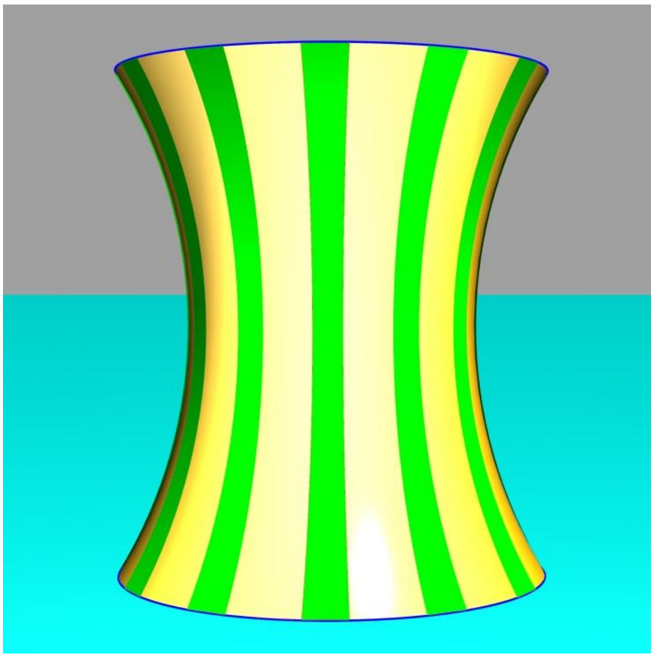


Figure 18. View of the best location of reinforcement strips following the method presented above.

5.3 Method to define the right combination of reinforcement and main membrane types.

Here we will present a mechanical based method to optimize both properties of the strips and properties of the membrane. It refers to the results of the testing machine of this research for defining the stiffness of the reinforcement strips.
Before explaining this method we have to make statements on the mechanical behaviour of the strips:

First Material Statement

A strip cut out of a coated fabric has his maximal strength if it is oriented parallel to warp or parallel to weft.

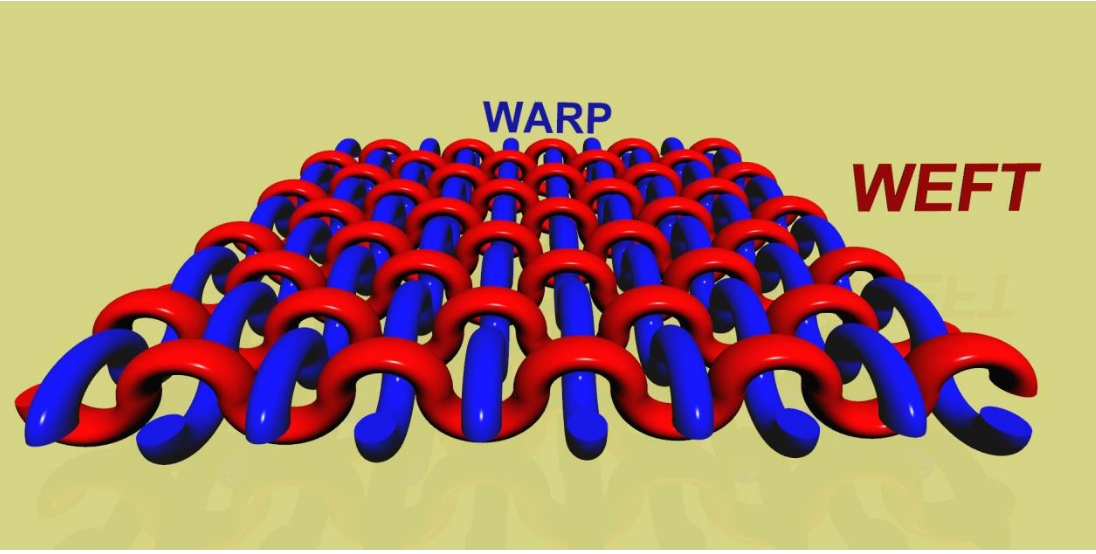


Figure 19. Example of textile with the two direction of the fibres

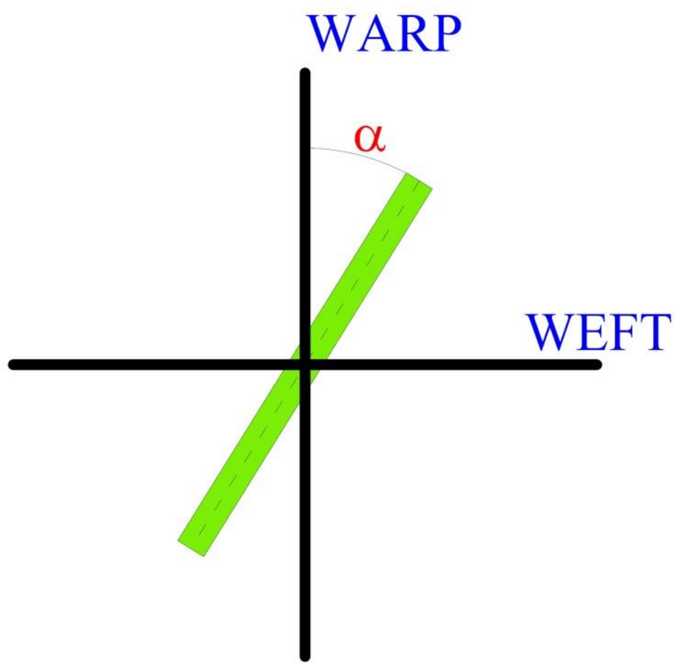


Figure 20. Presentation of a strip tilted with an angle α respect to the warp axis

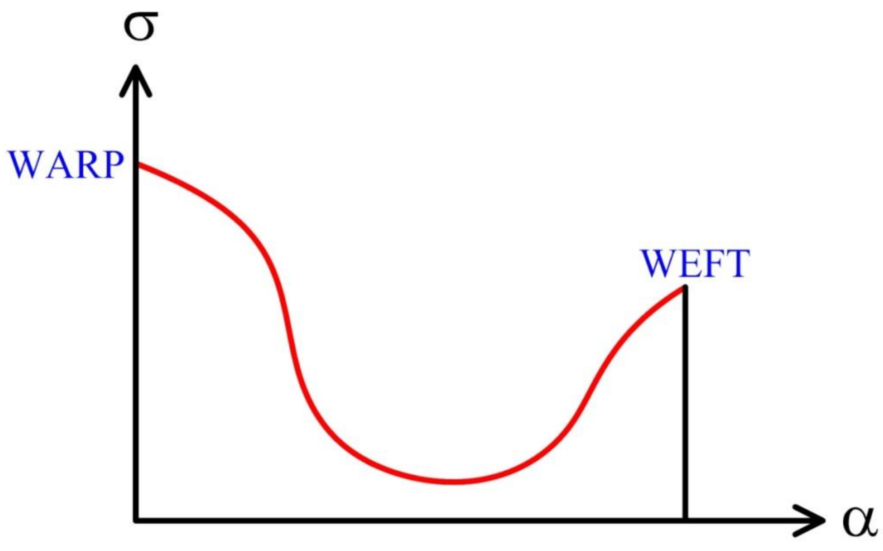


Figure 21. Variation curve of the strip stress resistance respect to angle α

Second Material Statement

If one combines two materials with different stiffness, so that they have same elongation in loading, the stiffer material will attract the force. Thus if we combine a strip of stronger material to a membrane, then the stronger material must have the higher e-Modulus. Otherwise it will not attract the stresses.

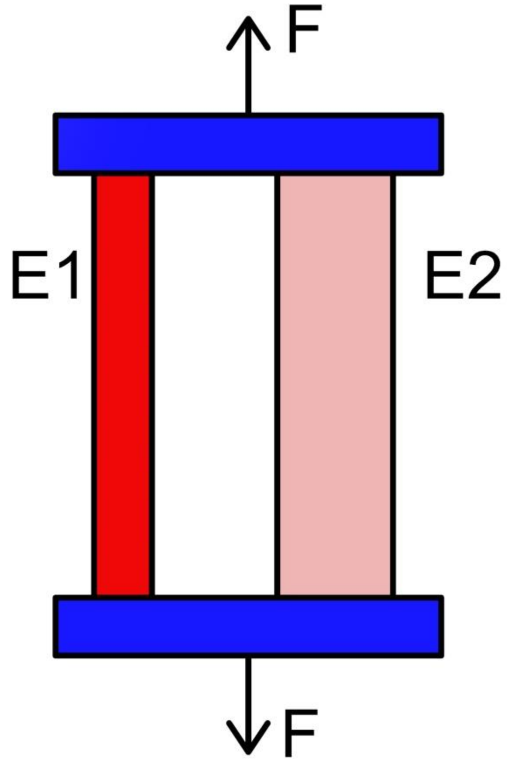


Figure 22. Example of two membrane with different stiffness under the same elongation

In the figure above two membrane strips are shown connected in parallel with two anchor flanges bolted at the edges.
Membrane strip 1 has elastic modulus $E_1 > E_2$ elastic module of Membrane 2
If on the flanges is applied a force $F = F_1 + F_2$ there will be an elongation $\varepsilon = \varepsilon_1 = \varepsilon_2$
Using the relation between Force, Elongation and E modulus we have the following:

$F_1 = \varepsilon * E_1$

$F_2 = \varepsilon * E_2$

$F = F_1 + F_2 = \varepsilon * E_1 + \varepsilon * E_2 \quad => \quad F = \varepsilon * (E_1 + E_2)$

$\varepsilon_1 = \varepsilon_2 \quad => \quad \frac{F_1}{E_1} = \frac{F_2}{E_2} \; => \; \frac{F_1}{F_2} = \frac{E_1}{E_2}$

From the last equivalences it is possible to understand that the stiffer membrane (the one with the higher E modulus) will attract more force than the weaker membrane sample proportionally to the $\frac{E_1}{E_2}$ ratio.

Third Material Statement

The E-modulus of a coated fabric measured in biaxial loading is higher than the one measured in uniaxial loading.

Thus it can happen that the E-modulus of the biaxial loaded fabric might be higher than the one of the reinforcement strip. Then the reinforcement strip will not take over the load. In this case one can pre-stretch the reinforcement strip at higher temperatures so that the first elongation will creep out. One can fix this creep elongation in cooling down the temperature while still loading the material. Thus the creep elongation will be fixed.

So using the steps of eliminating the creep elongation on the reinforcement strips it allows to load the combined system in a way to let both membrane work in parallel optimizing the combined stress result.

5.4 Defining the best location of the reinforcement strips in respect to the membrane welding.

Once respected the previous geometrical definition of the best paths to choose for the reinforcements there is one more factor to consider before setting the final position. That is the distance and symmetry of the location of the reinforcement in relation with the pre-defined membrane main welding. The safer solution is to place the reinforcement centrally respect to the membrane panel dimension and equally distanced from the welded edges.

This solution, that can be applied more easily on symmetrical covers, enhances the strength of the reinforced material. In fact there is always to remember that even the membrane main welding are reinforcement strips that can carry some tangential forces tensions due to the increased stiffness of the double membrane layer that could weaken the system if placed too close to the reinforcement strip. In the worst case this side effect could increase the stresses acting perpendicularly to the welding in some concentrated points with a weakening effect on the welding breaking point.

This negative effect will also be incremented if the reinforcement will be placed only on one side of the welding with an often easy to visualize effect of forming bad looking kinks or wavy looking wrinkles on the main membrane close to that area.

CHAPTER 6

AESTHETICAL EFFECT OF THE NEW SOLUTION

6.1 Aesthetical aspects of the patterning with membrane reinforcement strips

After having analysed the aspects of the mechanical resistance enhancement of the new reinforcement method, here we look at how this system can be chosen also to modify the aspect of the membrane cover.

As in the sketched figure 23 the simple four points sail can increase the stability against ponding and snow load adding a series of parallel strips placed around the upper two corner points direction (still having the precaution of not increase too much the tensions on the corner narrower edge to avoid membrane rupture). This action will not substantially change the pattern and the cut drawing of the main membrane while the result will be also easy to see from the cover user that will actually observe and understand where the membrane has to be stronger.

In this case the reinforcement could be also placed at increasing spacing distance between each strip, starting from that main upper line, so that the complete cover will look as bicolour with stripes that will enhance the tri-dimensionality of the main curvature.

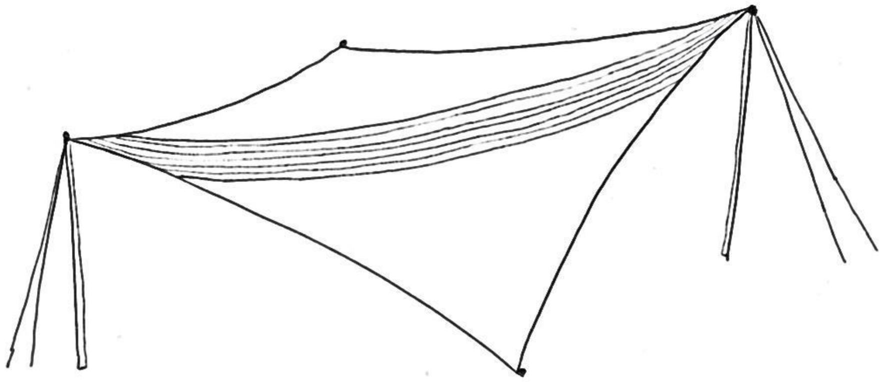


Figure 23. Four points sail cover with reinforcement strips on the most tensioned direction to reduce the ponding effect on the upper saddle curved surface

Without having to be too much creative, one immediate visual effect that the strips can add to the almost otherwise clear 2D “fake” aspect is the structural shading effect.

Like in the latest common use modern towers made of steel and glass, the main truss is often placed to be seen from the outside to add that texture to the building that moves the surface and gives special natural shading that change during the daylight. The unicity of a building is given by the main shape but also by that plethora of secondary shading and texturing effects often acting without the real planning from the designer architect.

If we look at the simple sketched figure 24, the simple architectural effect of looking at small “ribs” running down the cover, with the higher thickness of the reinforcement strips that makes small shades, increases that sense of permanency of the shape and almost underlines the physical presence of the building cover.

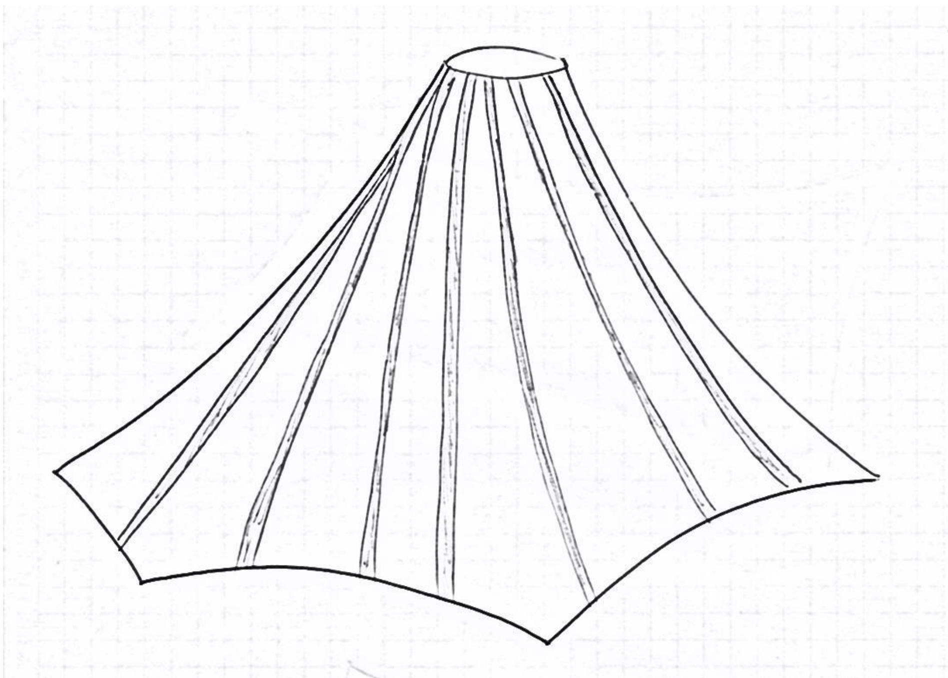


Figure 24. Conic over with central mast and reinforcement strips running parallel to the less visible smoother welding lines

One of the “problems” of the membrane covers is that their look of lightness often appreciated is on the other side a weakness point of view from the common people.

Environmental friendly architects and educated persons can seek to reduce the energetic path and the visual effect of their building by making it partially shaded or fully fabricated with tensile membrane. But unfortunately there is still a widespread consideration that people have of the membrane made covers as an ephemeral structure that could stay for weeks and then disappear to be dismantled like an old caravan tent. [9]

The architect sensibility should be to advance in the knowledge of the use of membrane different layers to create thickness and shades effects that give more volumetric aspect to the cover and more importance as a building that should have the same permanence of some other structures made in steel and glass.

Many decades ago Frei Otto made the “Dancing Pavilion” [10] in which over a relatively small installation there were multiple layers of overlapped membrane with different colours and light translucency that made a wonderful visual effect of multi shading environment. This light complexity effect under that cover constantly changing under the different hours of the day let the people living under this cover to feel the relaxing almost natural experience of being under the leaves of a bush. The risk on the other end is to exaggerate with the colour difference between different membrane layers that could result counterproductive to the aesthetics of the cover downgrading it to a circus tent look.

Besides the use of the standard belt-like PVC strips it’s possible also to play with the form of the reinforcement itself if the modified shape stays within some limits of form and mostly within some degree out from the main direction of the stresses.

In fact if we keep the central line of the reinforcement strip as in the position it should have using a constant width strip pointed in the direction of the warp as in the uniaxial testing of this research there is nothing that can prevent us from increasing the strip width as in the sketched figure n 25 hereunder. In some cases like here the resistance of the overall cover is even increased.

One limit that should be kept in order to work in a uniaxial prevalent direction is to limit the inclination of the strip width direction to few degrees of tilt from the main fibres direction, otherwise the influence of the other direction will have to be considered and all the result of this research will not be fully valid.

This assumption is even in theory correct due to the simple fact that once the working stresses are equally shared between warp and weft in a tensile membrane than the analysis of the behaviour should be made with biaxial testing machines that more closely can copy that mechanical field of work.

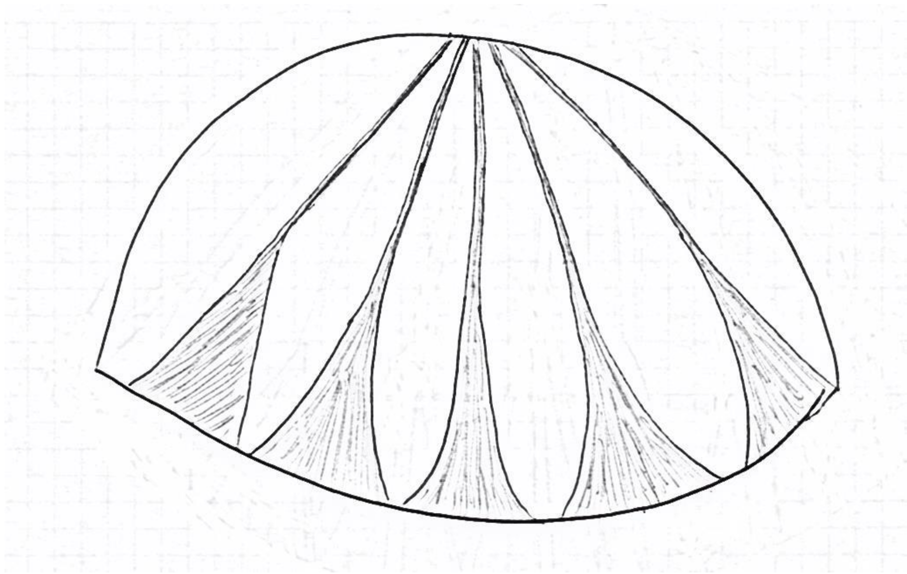


Figure 25. Spherical pneumatic building reinforced by strips with growing base width for aesthetical reasons and better anchorage to the perimeter

Following that prescriptions anyhow there is plenty of freedom in the choice of the patterns to be added to a cover with the reinforcement variable width strips. This enhanced freedom of shape gives to the architect a powerful tool to move the cover shape and to give more natural look to the otherwise straight “manmade” unmistakable sign of the membrane joints.

In the sketch above the reinforcement can become papyrus lives. In the sketched figure 26 it is possible to keep the belt-like strips but to weld them as an external perimeter of some geometrical shapes that gives to the eye the felling of a dynamical movement of the cover and also increase the complexity of the surface to look at.

6.2 From vaults to aesthetically functional reinforcement patterns

In the gothic cathedrals [11] the roofs where vaulted with the wonderfully crafted stone made ribs. This construction system strictly made in order to diminish the weight of the ceilings crated as a secondary effect a spider web like complex visual geometry in which the look of the visitors can lose itself in the joy of the contemplation of the heavenly orders.

Moreover in the tensile membrane behaving as vaults under opposite stress (membrane structures live only on tensile stress while in the vaults act only the compression stress) it can be enhanced the beauty of the rib like structures of the welding and also of the reinforcement strips playing with the geometrical symmetries.

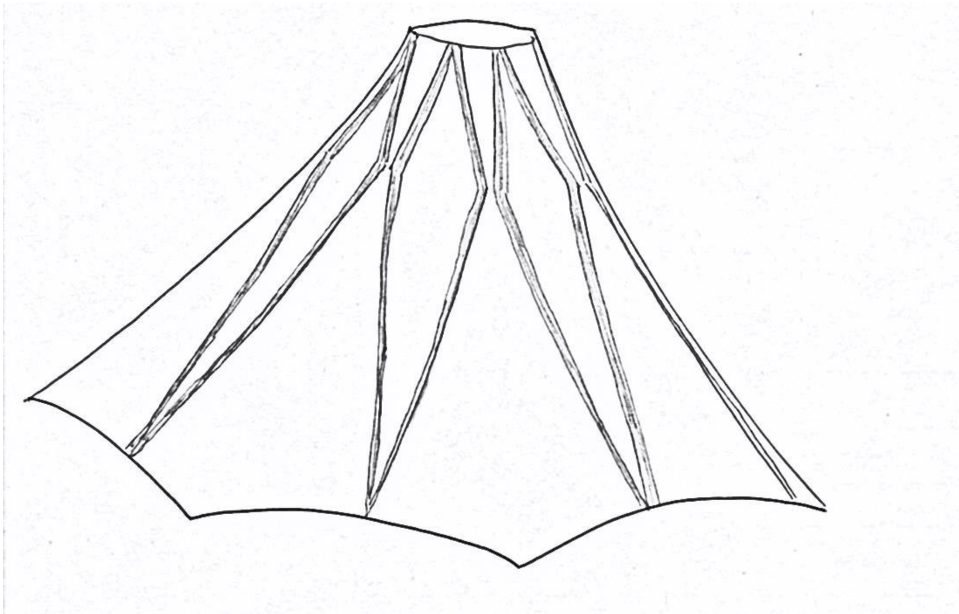


Figure 26. Conical single mast cover with more aesthetically modified reinforcement strips to slightly increase the stress resistance but more to create a geometric texture effect of jewellery craftsmanship

This effect can be also seen more closely in the following example of sketched figure 27 where the use of the strips is made only with easy made shapes that work on the main stress directions in order to increase the stiffness and resistance of the membrane under the wind and precipitation loads.

Here it is easier to understand that sense of magical geometrical complexity in the symmetry as in our middle age gothic religious buildings.

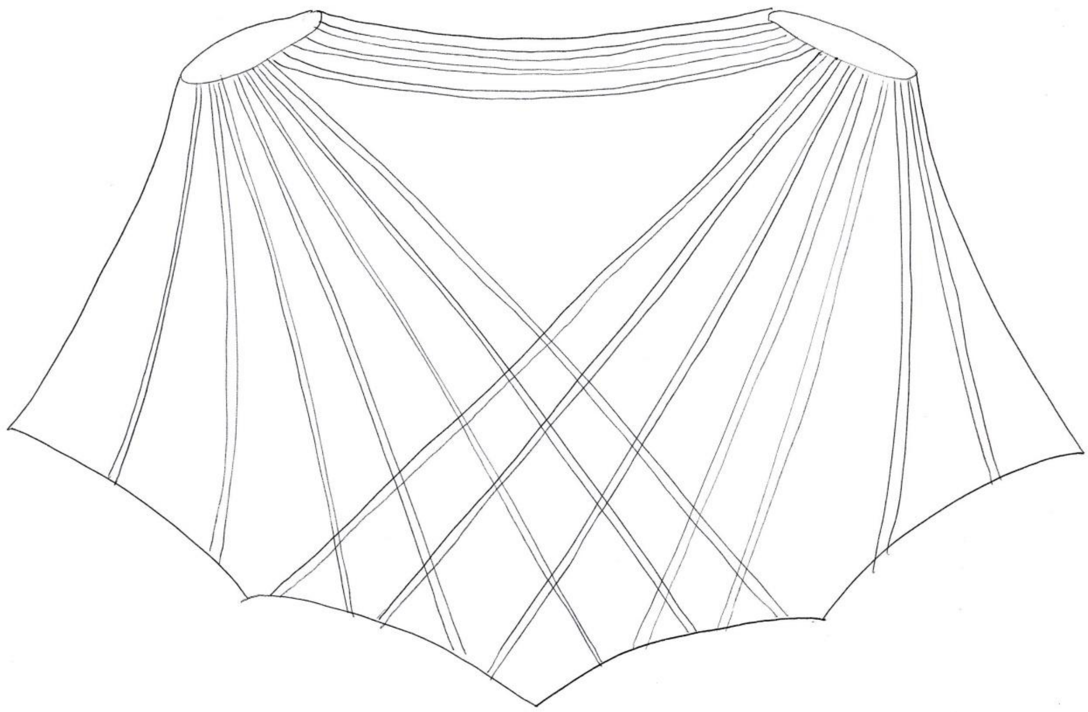


Figure 27. Double conical tensioned cover with two mast where the reinforcement strips act as stiffening elements to avoid ponding and excessive sag. The cross figure of the reinforcement lines works also as restraining net

In this example there is one more freedom grade that is to cross the reinforcements in a grid-like structure which will surely work in a biaxial field increasing the stiffness of the membrane in both directions.

The mechanical analysis of the behaviour of those crossing strips could be the subject of a future research using biaxial testing machines and also checking all the possible local stresses created by the interactions between main cover welding and crossing reinforcement strips.

This brief dissertation on the architectural aesthetical effects of the strips is by definition nonsufficient to show the almost infinite ways to "write" shapes on a cover using relatively simple and inexpensive materials and well known welding skills already needed by the manufacturer to build the main tensile cover membrane.

The aim of this chapter was to plant a small seed of curiosity in the minds of who will read this research so that they will be tempted to try to play with the shape of the membrane as usual in the lightweight membrane field but also to play with the reinforcements sheets.

CHAPTER 7

RESEARCH RESULTS OVERVIEW

7.1 Synthesis of the Research Results

In this short lines it will be summarized the results of the research with the evaluation of the tests done and already explained and analysed singularly on each membrane type in the Chapter 4.

Applying a reinforcement strip made with the same material kind (even with different thickness of fabric and coating) of the main polyester coated PVC membrane is clearly a successful solution.

In fact it has been here demonstrated that the use of specifically single layer reinforcement welded strips of 9 cm width made with a T3 or T4 placed over membrane from T1 to T4 resulted the best combination in both mechanical and economical terms.

Generally in the multiple test made it has been demonstrated that with that kind of reinforcement the membrane strength raises is mechanical stress resistance by a medium value of 20% respect to the basic one of the single working membrane.

Besides the increase of breaking point resistance that almost increased the Type of the reinforced membrane by one step (as from Type 1 to Type 2 or from Type 2 to Type 3) the most clearly visible effect has been the sharp increase of stiffness value of the tested reinforced samples specially at the lower tension stresses (that are still the one where the membrane is usually set to work).

The results shows that the reinforced material increases is stiffness by an average of 35 to 50 % respect to the non-reinforced single membrane.

One more interesting result of the research has been to greatly limit the successful combination of reinforcement strips with multiple layers that somehow against the expectations have been the source of a general diminishing of the stress resistance values of the sole membrane.

With the aid of a specifically designed test as in paragraph 4.14 and 4.15 it has been possible to demonstrate that the extreme difference in stiffness between a double layer welded reinforcement strip and the underneath main membrane sample cause the propagation of shear stresses. This increases the stresses locally along the border line of the welded strip with the result of weakening the whole membrane with a lower breaking point generation.

On the other end the best success in increasing both strength and stiffness of the reinforced material has been to use single layer membrane strips made with a Type n+1 respect to the Type n of the main material to reinforce.

This peculiar effect joints together the increase of performances of the membrane with the low cost of the solution applied.

The application of a Type 3 or Type 4 single layer welded strip is easy to make because the availability of the material can be found off the shelf from multiple membrane providers. Moreover it is quite easy to apply during the manufacturing phase without increasing too much the welding costs and with almost no increment in folding and packaging cost due to the slimness of the strip and of his relative low thickness.

7.2 Limits found during the research

As previously defined it has been found that this “new” reinforcement solution has limitations in terms of increase of stiffness and breaking strength due to the fact that is not possible to weld belts like reinforcement strips with a higher stiffness than the one tried with this new testing machine.

It has demonstrated that the use of a lower elongation strip creates immediately big shear stresses that cause the breaking of the reinforced sample. Therefore this technical new solution has a limited appeal in case of need to increase the resistance of the material more than a 30% of his typical values.

It has not been possible to check the amount of possible increasing/decreasing of the breaking point resistance of the samples in a more natural stress field working load as the biaxial geometry. For this reason the results achieved can be judged as partial respect to a wider field of possible loading actions that could even change the evaluation of the limits of the solutions applied.

One possible effect of a biaxial loading could be the reduction of the shear effect in one single direction, as is happening now, dividing it in two simultaneous directions where more textile can be set to work to carry out the extra loads. If this effect could be tested maybe it could be checked if this diffusion of the shear stress could allow the use of much more resistant and stiff two or more layers reinforcement strips with the result of increasing further the performances of the reinforced material.

7.3 Possible improvements of the technology under study

As previously described, this research results and methodology could be compared with the application in a biaxial loading geometry. To make that the sure problem will be to perform this task in a newly designed and surely much more expensive testing machine able to pull the material in both warp and weft up to the breaking point values.

The main problem of this biaxial machine is that in order to test the same size samples of the ones used in this machine made for the present research it would require the manufacturing of a 5 x 5 m biaxial machine where also the stresses should be applied in the same time as it happens during the real loading cases.

One more aspect that could be tested still with a machine similar to the one currently used is to see what benefits could be achieved with the use of even wider welded reinforcements strips. That could maybe result in an interesting increase of the mechanical performances of the materials without adding too much expense to the manufacturing of the solution.

One interesting improvement of the tested technology could be to apply the reinforcement strips in crossed direction as it can be partially seen in the sketch 27 in order to create a reinforcement net over the membrane able to partially restrain the elongations under biaxial stresses and to enhance the mechanical resistance of the whole cover.

This net-like reinforcement system should be a valid technical solution specially applied in the pneumatically supported membrane covers where the double curvature of the system together with the constant biaxial load exerted by the internal pressure is pulling the membrane in warp and weft with similar stress values.

One possible improvement of the current technology could be to look for new materials with a much higher stiffness value made with stronger fibres as Aramid or Vectran or Liquid Cristal Polymers or even considering the application of textiles made with carbon fibres. Those high tenacity textiles could be coated with PVC to form a single layer welding reinforced strip that could perform uniaxially following the paths here studied but they could allow the reach of much higher stress resistance to the underlying membrane.

The behaviour of those new materials reinforcement would allow the construction of reinforced membrane that would closely compete with cable nets in terms of working loads and still retaining also the good proprieties of a tensioned membrane.

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