APPLICATION OF THE FLEXOMETER-TEST ON MEMBRANE-FABRIC USED FOR RETRACTABLE MEMBRANE STRUCTURES

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Summary: *In this paper, the Flexometer-Test is described and applied to four different membrane materials. As part of this it is proven that the procedure is very suitable to simulate the stress a retractable roof puts on the fabric. Finally, the effect on these four samples is shown and evaluated through tensile strength and air tightness tests.*

1 INTRODUCTION

It is a well known fact that tents were one of the first kinds of housing mankind has developed. The ancient tents were small, but had the great advantage that they could easily be taken apart and mounted again elsewhere.
Nowadays people still like to be flexible towards weather conditions or other natural influences. Therefore stadiums and theatres are often designed with retractable roofs.
This kind of roof can be opened or closed with the help of electric engines and hydraulics. Its technique has created big challenges for the structural designers and it is still lively discussed which fabric fits best for retractable roofs.
Furthermore a standardized test procedure that recreates the conditions membrane material is subjected to when it is frequently folded and unfolded still has to be found.

As part of my Bachelors-Thesis research has been done in the leather and textile industry to find such a test. In the so called “Flexometer-Test”, the core of my research, a piece of cloth is folded in two directions at the same time. This creates a unique fault in the fabric that is vastly different from the one caused by simple folding and unfolding. Applying this test to various common products has lead to interesting results. Additionally, a first classification of these materials is proposed to help designers in evaluating the suitability of membrane material as a constantly moving element in a structure.

2 RESEARCH

During preparation for my thesis on retractable membrane roofs an extraordinary damage was found, shown in the following pictures. This particular failure of the material is very rare and could not be found in static structures.

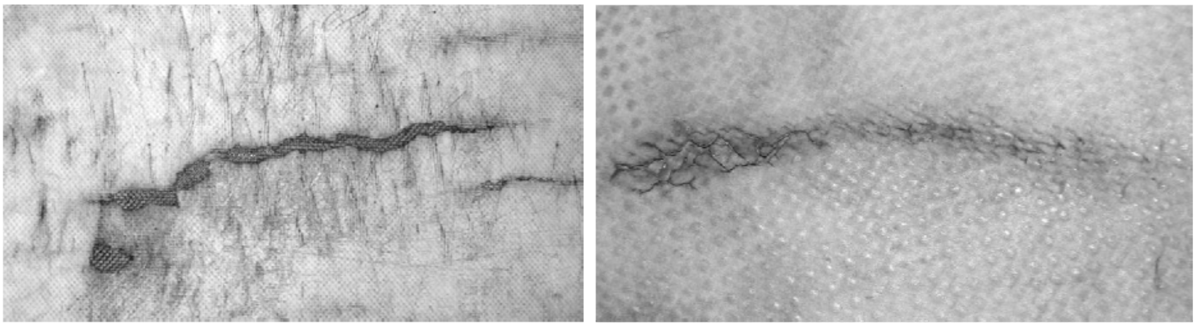

Figure 1: Damaged membrane fabric

Therefore, it can be concluded that constant folding and unfolding of membrane material has a great impact on its lifespan.

Most projects today undergo a certain amount of testing to make sure they will function over the intended time span. This may be done through mock-ups or additional tests of folding etc. Unfortunately, the demands and the methods are project-specific and there is no uniform basis on which membrane-fabrics could be categorized to make it easier for designers to choose the right product for the job.

Therefore, the task was set to apply a new and unique stress on different types of commonly used architectural membrane fabrics. Ideally, that test should give a more realistic portrayal of the real life situation and give a deeper understanding on what actually damages the membrane to decide where the design of retractable roofs could be improved.

To find a test that mimics the real situation well, one has to look at the damaging mechanism first. This table is a shortened version of the one, depicted in my thesis. It has been pooled from sources [1],[2]. Biological, chemical and physical influences have been dropped:

Table 1: Influences on retractable roofs

Status of the membrane		**Always**	**Closed**	**Opening/closing**	**Open**
Influences on the membrane	**Mechanical**	Self weight	Loading	Abrasion	Abrasion
				Moving & still kinks, folds and double folds	Moving & still kinks, folds and double folds

Every retractable roof has three stages: Closed, moving and open. A closed roof, meaning that the membrane is under tension and spans over its maximal size, is no different from any other static membrane roofing. Therefore, it does not contain kinks, creases or folds. So the critical stages are the moving and parking of the roof. When looking at an open roof where the fabric has been raffled to its center-point, it can be found that kink folds form. The stress that is forced onto the material is enormous and there can be no doubt that this crumpling is what reduces the webbing's strength.

Figure 2: Parked retractable roofs; raffled to their central point (Kink folds are marked)

When looking for a test procedure that would model that kind of behaviour, my research began in the database of standardized material tests of the textile industry, that contains almost 1000 entries. After ruling out all colour-, tightness- or abrasion-themed tests and solely focussing on crumpling, folding etc. a small group of tests remained. When investigating in other industrial branches, for example convertible roofs for cars, it could be found that most products were tested on a varying series of this same, small group of experiments. With little expectations on finding more procedures no further research was done. Besides there was already a test that protruded from the others. It appeared to mimic the exact stress of moving kink folds the way they emerge in retractable membrane roofs. The so called "Flexometer"- or "Bally"- Test therefore became the basis for the rest of my research. To my knowledge, this test was never applied to synthetic membrane material.

3 THE TESTING PROCEDURE

The Flexometer-Test appeared to be more suitable than simple folding and unfolding procedures or the crumpling tests because the damage inflicted on samples, closely resembled the images of damaged retractable roofs. Moreover, does its mechanism reduce crumpling to its most damaging element, which is moving kink folds. This way it creates a very controllable and so reproducible stress onto the sample. This is not the case with the other crumpling-tests.

The machine consists of a fixed lower part and a moving upper part. The moving clamp performs a twist of 22.5° around axis A at 100±5 cycles per minute, whereas the lower clamp remains immobile.

In the standard this description of the test is given: A sample is folded and fixed in the upper clamp. The remaining part of the probe is folded in the opposite direction and fixed in the lower clamp. When the upper clamp moves, a running crease is created within the material. The sample is periodically checked for damage.

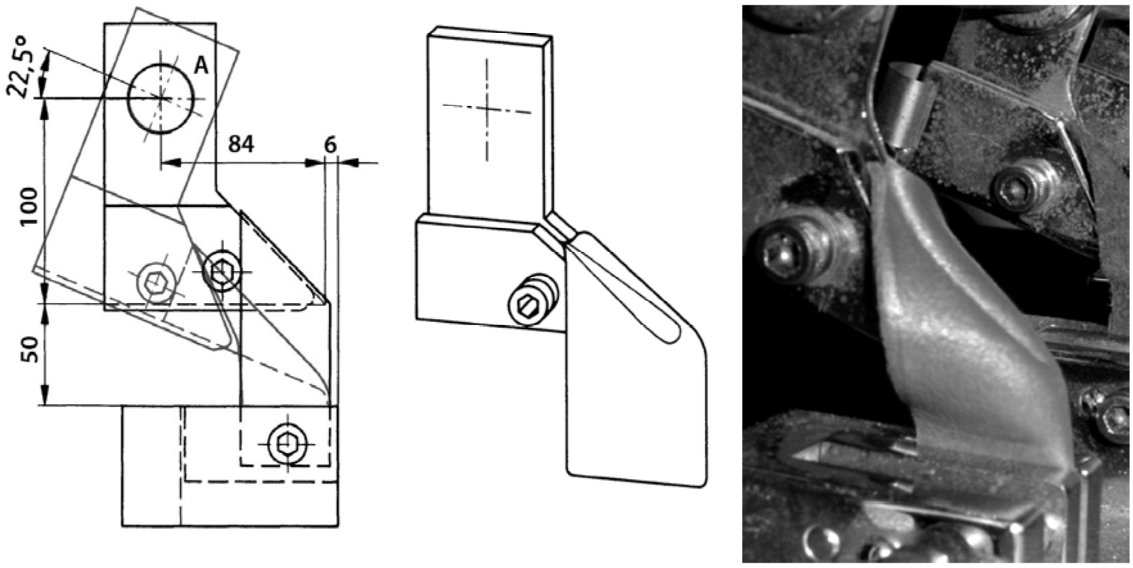

Figure 3: Comparison: Technical drawing & machine as used for leather

This way a kink fold is created and moved over the same area, causing tremendous stress and therein resulting slow dismemberment of webbing and coating, or destruction of one or both of these components.

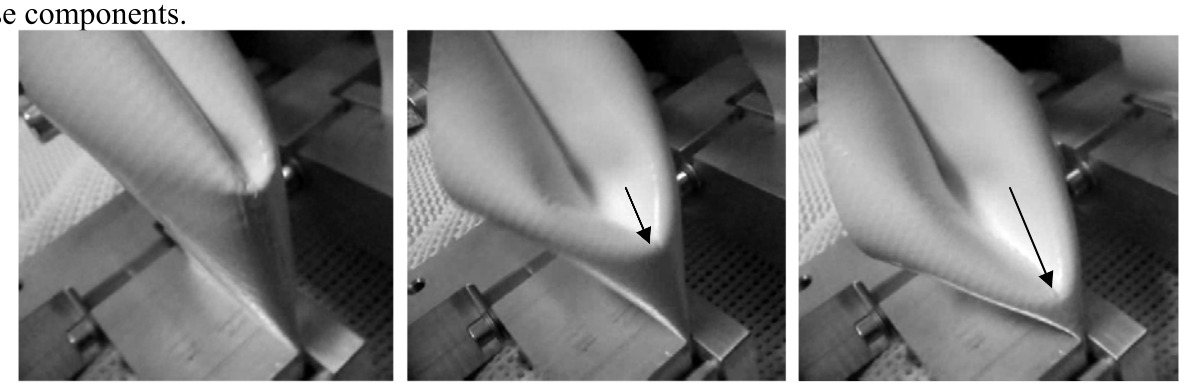

Figure 4: Stages of motion: PVC-coated PES material, fixed in my scaled Flexometer
(Kink fold moves up and down the fabric when the clamp twists)

The standard suggests the following amounts of cycles after which the sample should be checked for damage.

Table 2: Folding cycles, according to DIN EN ISO 32100

-	200	315	500	800
1250	2000	3150	5000	8000
12500	20000	31500	50000	80000
125000	200000	315000	500000	-

The numbers are based on the so-called "Renard"-Series with its factor m equal to 10. So the term is the tenth root of ten to the power of X. Unfortunately, it is not stated why this series of numbers was chosen.

$$R_{10} = (\sqrt[10]{10})^x$$

To comply with the standard as much as possible, these suggested numbers of cycles were adopted by me. The same applies for the climatic conditions. All tests were carried out at approximately 23°C and 50% relative humidity.

After building a mock-up of the machine, the first tests were done and the concept of the machine's mechanics proved to be as expected. The intended damage could be seen in several small test strips, but not in all. Therefore, the first conclusion could be made that the test also works on membrane material but not reliably. Additionally, the strips appeared to be very small and posed the question if such a small damage would cause significant reduction of strength. The pictures taken from actual failures showed a much larger affected area.

So when assessing the first results, the decision was made to build another mock-up in a 2:1 scale from the proposed measurements of the standard. Combined with rounded edges, great results could be achieved with the machine and a larger fault proved to be reproducible with great reliability.

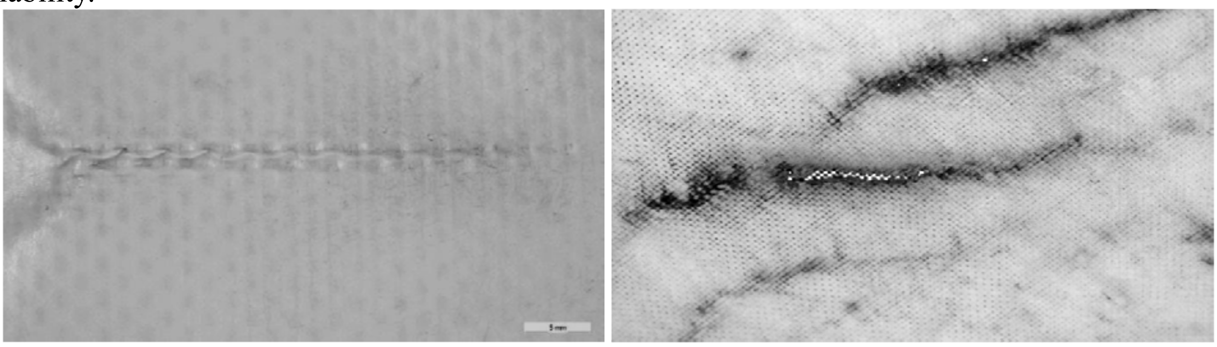

Figure 5: Comparison: Flexometer-sample & actual damage

To determine the loss of structural integrity as well as tensile strength, additional tests had to be imposed on the material before and after the treatment in the Flexometer.

The loss of strength was set to be measured with a simple monoaxial tensile strength test that stretches a sample with a preset, constant speed until it ruptures. The force at which the strip fails is the measured value of tensile strength. To account for scattering, several tests had to be done and the 5%-fractile of the results could be compared. With three of these results it would be possible to draw a graph of tensile strength relating to cycles in the Flexometer.

For the loss of tightness towards penetration through rainwater it was proposed to use a test of water-tightness that unfortunately was not available on short notice. Therefore an air-tightness test was applied that, combined with comprehensive microscopic investigation, proved to be sufficient enough to derive acceptable conclusions from.

On this basis the first tests could be performed

4 TESTING PHASE

The company “Eccon”, located in Austria, which is also greatly involved with retractable roofs, fabricated a scaled Flexometer machine for me, according to my specifications. With it, it was possible to test several materials for their resistance against kink folds.

With this machine my research could go into its practical phase. Having been provided with various materials such as PTFE-coated glass fibre webbing, Silicone-coated glass fibre webbing, PVC-coated PES webbing and PTFE-coated PTFE webbing (Tenara), sponsored by "Verseidag", "Koch" and "Sefar", it was possible to get a direct comparison between the most commonly used combinations of types of coatings and weaves.

However, at this point it was still unclear how many times the material would have to be folded to see an effect in each of the fabrics. Additionally, in case that number was found, how should be determined whether it corresponded with the stress of real structures.

To answer this question it has to be decided when the creasing causes the greatest damage in real life situations. On one hand, it can be argued that kink folds form when the roof is moving. As they appear, they move within the fabric and may cross each other, creating even greater stress. The engines are computer-controlled and perform exactly the same motion with each opening or closing of the roof. So one could imagine that the creases always form the same way and slowly worsen the condition of the weave with every time it is moved. The basis of that argument is that once the roof has come to rest in its garage, there is no further movement. But on the other hand, one could say that wind, as well as changing of temperature or vibrations in the structure could induce swaying of the garage and the parked membrane within. The consequence would be a constantly moving crease over a confined area, resulting in multiple times the damage of creasing during opening and closing.

While both concepts are based on the same failure, they both bear a fundamentally different consequence for the outcome of the testing. That is because, if one assumes that creasing only happens during the moving phase, the result is that there are roughly going to be about 500 times that the folding and unfolding occurs. That equals to 20 cycles per annum over an estimated service life of 25 years. Whereas there is no way of accurately telling how many times the material is going to sway and how many times the fold will move during the closed stage. But it can be safely assumed that the movement is going to be a lot more often.

After having figured out how the material has to be fixed in the machine so it does not get damaged through handling or unwanted kinking, first tests had to be carried out to determine the inflicted damage. The most important question at the time was how many cycles the machine has to perform to inflict damage on the material.

To document the effectiveness of the procedure and to show that it can also be used on all kinds of membrane material, several different products were fixed in the machine. The Flexometer was then switched on and started running through the whole spectrum of proposed cycles from the standard. After every listed number of foldings the effects were documented for later use. After 31500 cycles even the last fabric showed a significant change in the webbing or the surface and the test was finished.

Under a heat-detecting camera, it could be seen that the movement causes great heat within the material. That is through friction between the webbing and the coating. It slowly dismembers the components and causes the composite to disintegrate.

(f.l.t.r.): PES-PVC I / Glass-PTFE / Tentickle-material / PES-PVC II / PES-PVC IV

(f.l.t.r.): Glas-Silicone / uncoated PTFE-webbing / PTFE-PTFE / PES-PVC II / PES-PVC II

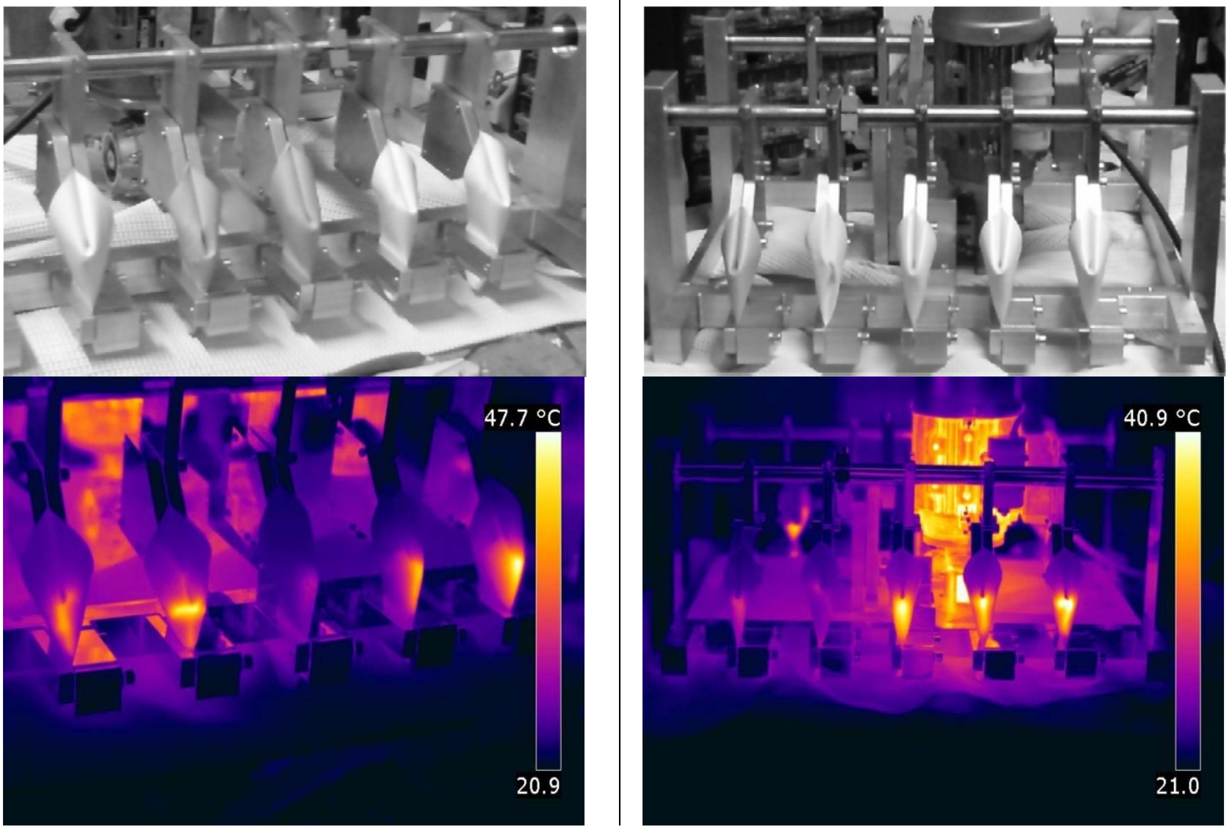

Figure 6: Heat-development caused by the Flexometer (after roughly 20,000 cycles)

The next aspect that had to be figured out was in which direction to the folding, the tensile strength was to be tested. Considering that membrane structures usually have a biaxial strain the first idea was that the tested strip had to be stretched orthogonally to the direction of folding. Especially if one looks at the number of threads, damaged through the Flexometer, there is a much larger area covered in the direction of the folding. So there would not be only one to three damaged threads, but up to 50. It was anticipated that the reduction of strength was going to be far more significant in that direction. This proved to be mainly true. But fixing the samples properly, as well as finding a shape for the samples that allowed them to fit in the Flexometer, as well as the tearing-machine posed great challenges that could not be overcome properly. This was also observable in the test-results which showed large scattering. Ripping the samples in the same direction that the folding had happened was far simpler and also lead to satisfying results. It was therefore the favoured method to give a first insight on what the test does to the material. Further research on how to tear the samples in a 90° angle to the folding may lead to better results and probably even a different outcome of the tests, but were not part of my thesis.

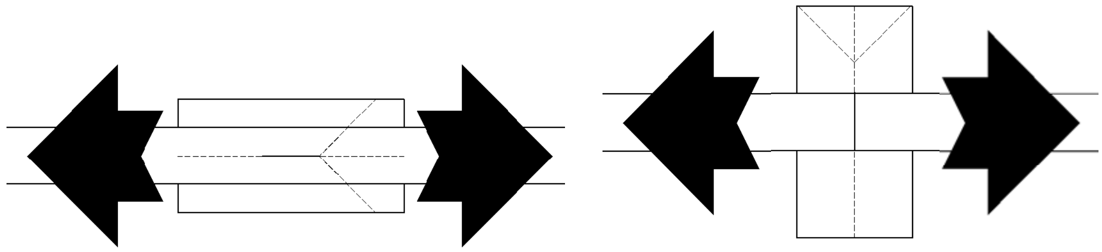

Figure 7: tensile strength in fold-direction and orthogonal to it

With the acquired information the following final test series was set to document how the materials react to the treatment in the Flexometer. Unfortunately, the area of PVC-coated PES fabric and silicone-coated glass fibre material given to me was not large enough to cut out 5 samples for each test.

Table 3: Samples, used for the final test

Material	Reference (0 cycles)	3150 cycles	12500 cycles
PTFE/PTFE – warp	5 Samples	5 Samples	5 Samples
PTFE/PTFE – weft	5 Samples	5 Samples	5 Samples
PES/PVC – warp	4 Samples	3 Samples	3 Samples
PES/PVC – weft	5 Samples	4 Samples	4 Samples
Glass/PTFE – warp	5 Samples	5 Samples	5 Samples
Glass/PTFE – weft	5 Samples	5 Samples	5 Samples
Glass/Silicone– warp	5 Samples	5 Samples	5 Samples
Glass/Silicone– weft	0 Samples	0 Samples	0 Samples

Despite the inconsistence of sample-quantities it was possible to draw a graph, showing cycles and corresponding tensile strength. This way the decline of strength is easily observable as well as comprehensible.

As mentioned before there was no time to inquire the loss of water-tightness in depth and therefore only one test for each material and number of cycles could be conducted. Additionally, the test, used for this data did not work as planned and what can be seen under a microscope is not backed by the data. More information on that is given in the following section.

After carrying out the tests, the following results could be obtained:

Table 4: All test results & statistical analysis

		PTFE/PTFE			PES/PVC			Glass/PTFE			Glass/Silicone		
Warp	**Cycles**	**0**	**3150**	**12500**	**0**	**3150**	**12500**	**0**	**3150**	**12500**	**0**	**3150**	**12500**
	Sample1 [N/mm]	110	109	100	92	83	63	143	75	53	144	37	45
	Sample2 [N/mm]	109	109	103	95	83	67	145	66	71	141	38	37
	Sample3 [N/mm]	112	110	106	91	85	59	142	69	76	146	39	51
	Sample4 [N/mm]	113	110	105	93	-	-	144	80	62	136	49	44
	Sample5 [N/mm]	112	108	101	-	-	-	131	71	73	145	48	42
	arithmetic average [N/mm]	**111**	**109**	**103**	**92**	**84**	**63**	**144**	**72**	**70**	**143**	**49**	**44**
	Variance [N/mm]	1.64	0.45	5.78	2.89	2.24	14.61	2.37	29.28	36.37	16.27	0.10	25.12
	Standard deviation [N/mm]	1.28	0.67	2.40	1.70	1.50	3.82	1.54	5.41	6.03	4.03	0.31	5.01
	Standard deviation [%]	1%	1%	2%	2%	2%	6%	1%	7%	9%	3%	1%	12%
	5%-Fractile [N/mm]	**109**	**108**	**98**	**89**	**80**	**54**	**140**	**61**	**58**	**134**	**48**	**33**
	Loss of strength [%]	**0%**	**1%**	**10%**	**0%**	**10%**	**39%**	**0%**	**52%**	**55%**	**0%**	**65%**	**75%**
Weft	**Cycles**	**0**	**3150**	**12500**	**0**	**3150**	**12500**	**0**	**3150**	**12500**			
	Sample1 [N/mm]	119	113	106	98	82	74	147	79	54			
	Sample2 [N/mm]	115	114	105	98	85	75	141	60	62			
	Sample3 [N/mm]	114	114	107	99	85	76	139	82	58			
	Sample4 [N/mm]	115	115	107	98	83	70	145	78	59			
	Sample5 [N/mm]	107	114	107	98			141	79	44			
	arithmetic average [N/mm]	**116**	**114**	**106**	**98**	**84**	**74**	**143**	**80**	**58**			
	Variance [N/mm]	5.27	0.32	0.92	0.13	2.26	6.54	9.11	2.13	10.54			
	Standard deviation [N/mm]	2.30	0.56	0.96	0.36	1.50	2.56	3.02	1.46	3.25			
	Standard deviation [%]	2%	0%	1%	0%	2%	3%	2%	2%	6%			
	5%-Fractile [N/mm]	**111**	**113**	**104**	**98**	**81**	**68**	**136**	**76**	**51**			
	Loss of strength [%]	**0%**	**-2%**	**6%**	**0%**	**17%**	**30%**	**0%**	**44%**	**63%**			
Tightness	**Cycles**	**0**	**3150**	**12500**	**0**	**3150**	**12500**	**0**	**3150**	**12500**	**0**	**3150**	**12500**
	Warp [inch]	40	9	7	40	40	8	40	21	0	40	0	0
	Weft [inch]	40	40	7	40	40	40	40	14	2			
	Warp [mm]	1016	216	183	1016	1016	1	1016	533	0	1016	0	0
	Weft [mm]	1016	1016	165	1016	1016	1016	1016	356	38			

Despite all effort, faults did occur in the running crease especially with the delicate glass-weaves. This lead to strikingly different results in strength and so the results had to be dropped from interpretation and are marked in the table above.

The therein resulting 5%-fractiles of all strength-values give information on how the material reacts on the Flexometer-procedure.

5 INTERPRETATION & CONCLUSION

Visualizing the obtained data as a function of cycles in the Flexometer in graphs looks as follows:

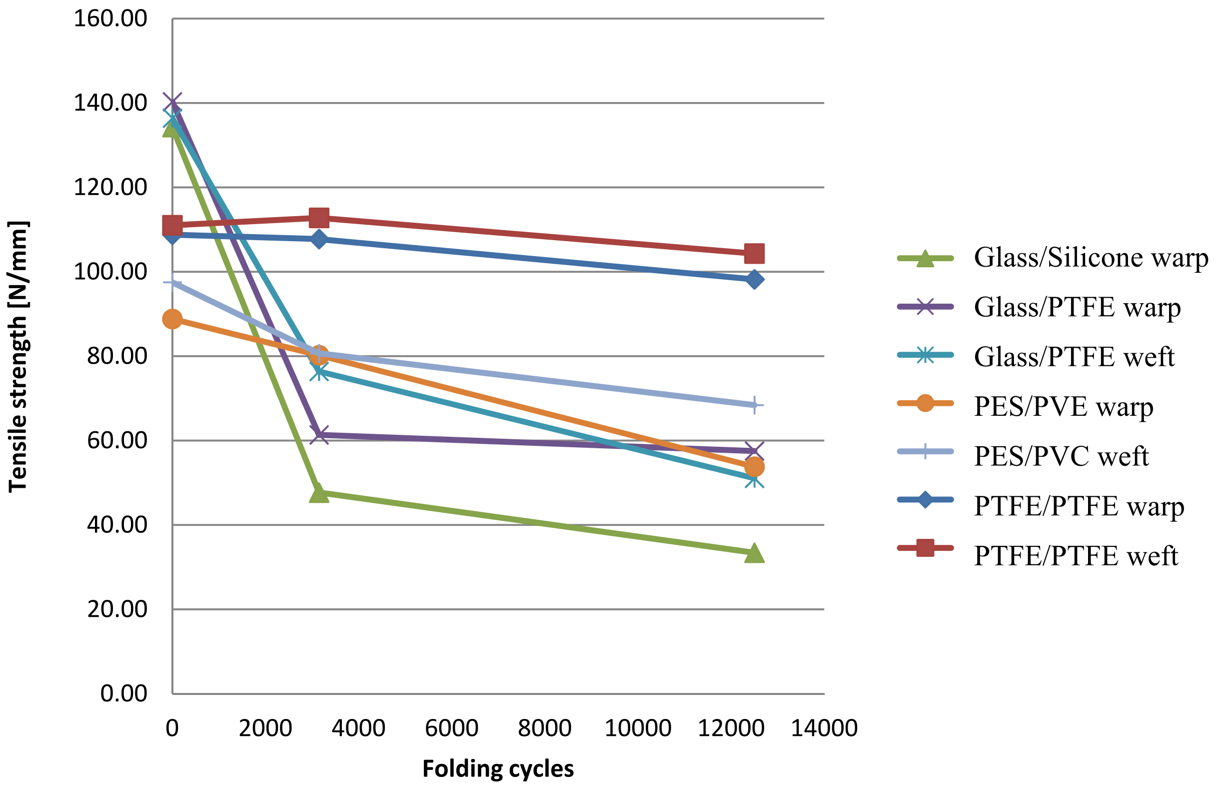

Figure 8: Folding cycles and corresponding 5%-Fractile results

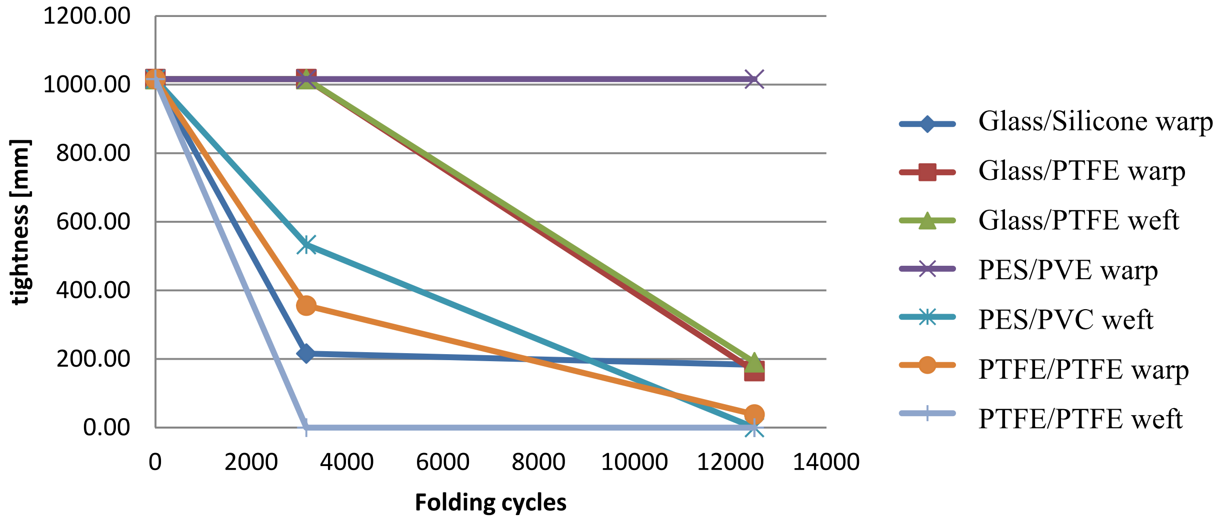

Figure 9: Folding cycles and corresponding air tightness values

As expected, the fibreglass webbing ruptures after a few cylces. After 3150 cycles, the tensile strength of the material has decreased over 40%. As one can see under a microscope, the filament is completely destroyed where the folding has taken place. The remaining strength comes from the intact fibres left and right to the crease. If strain was to be applied under a 90° angle, the strength measured would be only tear strength. The material can be seen as broken and should not be used. The radius of the redirection, caused by folding, is too sharp for the material and it breaks. It is not suitable for retractable roofs; the coating does not make a difference at this. Both the PTFE as well as the silicone coated webbing behave the same way.

The PTFE as well as the PES webbing behave differently. Both decrease very little in strength, which shows that this materials are more suitable for retractable roofs than fabric from glass fibres. When looking at the decrease in strength one finds that the PES fabric overall loses more load bearing capacity than the Tenara. It seems that of all tested products, the fabric made from PTFE-monofile fibres is the one best suitable for retractable roofs. When looking at the air tightness, a different outcome is imposed. Where the Tenara loses resistance against air penetration after few cycles, the PES performs nicely. As mentioned before, the tightness test was performed in a rush for deadline reasons, so there was not enough time to have a sufficient number of samples. Therefore, the results are not definite or representative. But when looking at the pictures taken under a microscope the reason for the large scattering can be found.

The PTFE coating almost instantly starts to have micro-cracks in the coating. Tiny cracks, only micrometers wide appear on both sides of the yarn. Therefore a passage through the material is formed, wide enough for air to pass through. Whether it is big enough for a capillary action to occur is unknown. But it is obvious that dirt and mould are given a rough surface on which to attach to with ease. The reason why the PVC-coating performs so well is also unveiled under a microscope. The coating gets continuously thinner through the Flexometer. But the surface remains intact until it finally ruptures and leaves a large hole. As soon as this happens, the entry into the load-bearing part of the composite material is open and all sorts of foreign objects as big as a pinhead are able to enter the membrane. Further studies on this matter should give a better understanding on which coating is more suitable to withstand folding.

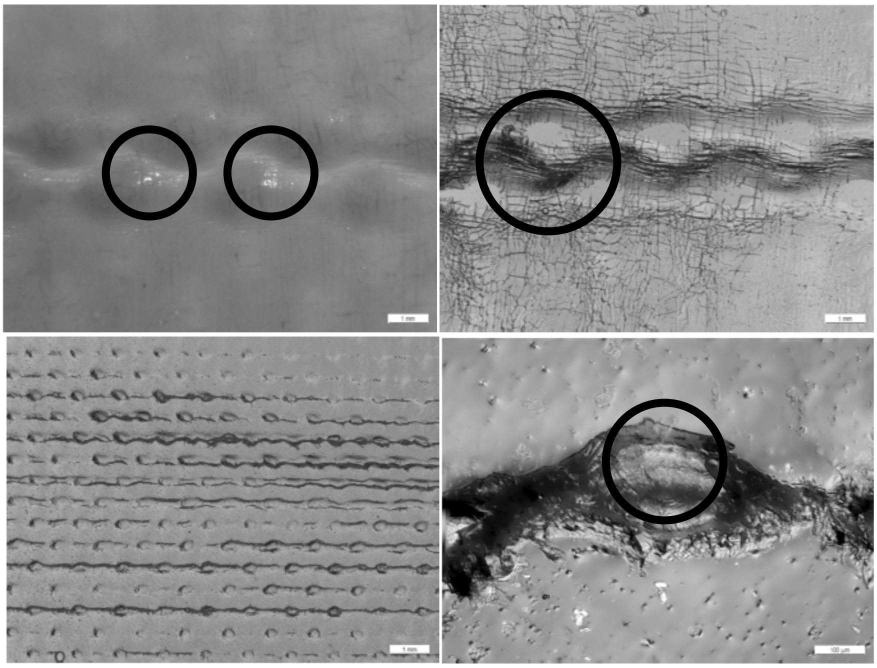

Figure 10: Transmitted light microscopic image and details of two sample's surfaces (PES/PVC: weakened spots marked; PTFE/PTFE: missing coating marked, thread visible)

In conclusion, it can be said that the Flexometer test is very suitable for the task of determining the resistance of membrane material against kink folds. If agreed on common requirements, it could be used to categorize available products, which ultimately will lead to a better feasibility and reliability of retractable roofs. However, the appropriate number number of cycles still has to be discussed.

The potential of the test is still not exhausted. For testing under extreme climates may lead to a significantly different outcome and conclusion about the material's suitability. The same is true for artificial aging before folding.

Looking at the results of the tightness tests it can be said that it does not work the way it was attempted in this study. If one was to stretch the material with a service load after folding it, the coating may fail sooner, giving fluid a chance to enter the webbing. Under this point of view a test for wicking is probably more significant than tightness, where both layers of coating have to fail to achieve a reduction of the measured values.

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