BEHAVIOUR OF INFLATED FABRIC BEAMS AT MEDIUM PRESSURES

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SUMMARY: The aim of the paper is to display experimental and numerical results on the behaviour of inflated fabric beams (panels and tubes) submitted to bending loads. These structures are inflated at medium pressures (about several bars) in order to ensure very good strength abilities. Panels are made of two coated linen cloths connected by yarns in order to ensure a perfect flatness, and tubes are made of simply coated fabrics. The behaviour of the structures depends on the inflation pressure which leads the cloths and the yarns to be prestressed. These structures are very light, easily transportable and extremely strong. The shape of the deformed structures is linear between points of loading. It seems therefore that they behave as tight yarns, but it is shown that a yarn model gives valuable results on the deflection when the pressure is low, but very bad results for higher values of this pressure. A beam model is not suitable to calculate deflections because of the less of curvature, but gives a correct answer for the collapse load. Modelling of these structures suppose computations with hypothesis of large displacements and following forces.

KEYWORDS: inflated beam, pneumatic, textile, following forces, medium pressure

INTRODUCTION

The paper is devoted to the analysis of the behaviour of inflated structures submitted to medium pressures (about several bars) because such studies do not exist yet. Inflated structures are generally used at low pressures (lower than one bar) and their mechanical behaviour is not the main interest of engineers because these structures are not able to support heavy loads. The work introduced here is devoted to fabric beams submitted to pressures varying from one to several bars in order to ensure a strength behaviour. The first step is the study of flat panels and tubes. Panels are made of two coated linen cloths connected by yarns in order to ensure a

perfect flatness, and tubes are made of simply coated fabrics. The tested structures are a simply supported "beams" loaded by a concentrated force. We will show that the behaviour of theses beams is surprising: the bending shape is linear between points of loading, which proves that these "beams" are not beams when the pressure is greater than one bar! The first results on tubes have been published by Main & al [1] and they have shown that inflated tubes behave like beams, which is true because their study has been done with tubes submitted to a low pressure. In the case of inflated panels, the first studies can be found in Wielgosz & al [2], [3]. This paper is devoted to display experimental and numerical results on the behaviour of inflated tubes.
We will show that the usual simplified models of the theory of strength of materials like a tight yarn model or a beam model (because of the less of curvature), are unable to give a correct value of the deflection of one of these beams when the pressure is greater than one bar. A beam theory gives yet a good approximation of the collapse load of these structures, because in a limit load analysis, the collapse mechanisms satisfy linearity between plastic hinges. These results show that we must construct a new theory for the analysis of inflated structures at medium pressures. This work must be achieved. The second way is to use numerical computations. We will show that the real behaviour of these structures can be obtained with the finite element method and with the following hypothesis: cloths are membranes in tension and allow large displacements, connecting yarns (for the panels) are non linear bars, and the pressure is replaced by following forces applied normally to the cloths. All the numerical computations have been done with CASTEM 2000 [4]. Meshing must be very fine just about the loading point and the supports in order to take into account local effects. Strength abilities of the structure are given by buckling conditions of cloths.

EXPERIMENTAL RESULTS

Inflated panels

A section of the panels made of two coated linen cloths (polyester) connected by yarns is shown on Fig. 1 and provides from Tissavel's tract.

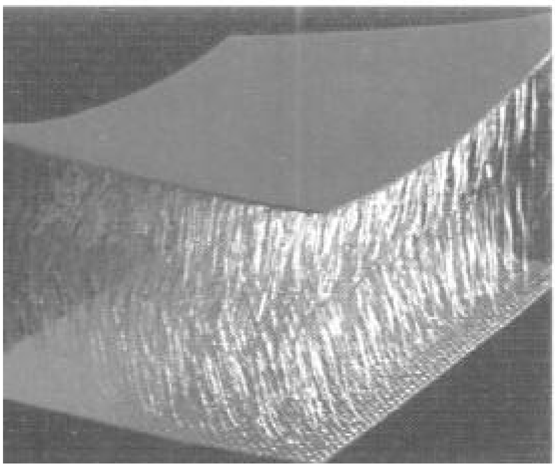

Fig. 1 : cross section of the panels

The yarns density is enough to ensure the flatness of the fabric structure. Its behaviour depends on the inflation pressure which leads the cloths and the yarns to be prestressed and then to support local compression loads.

Bending shape

Many panels have been tested and the results are given for one of them. Its length, width and height are 200, 25, 5 cms. It's a simply supported "beam" loaded by a concentrated force and the length between the supports is about 160 cms. The inflation pressure will vary up to 4 bars. The shape of the deformed panel submitted to a bending load is shown Fig. 2.

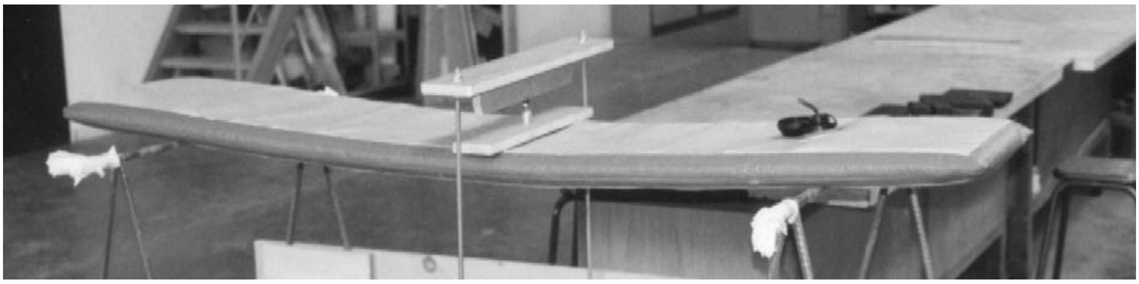

Fig. 2 : bending shape of a panel

One can see that the bending shape is quasi linear between points of loading and that the free ends of the panel remain straight and almost horizontal. In fact, light curvatures appear near loading areas (supports and loading point). The panel has therefore a tight yarn behaviour and not a beam behaviour.

Limit load

The limit load is a linear function of the applied pressure and is given Table 1.

Table 1 : Experimental limit load as a function of the pressure for the panel

p (bar)	1	2	3	4
F_l (daN)	9	19	28	38

The weight of these structures is only about a few kgs and their limit load can reach a hundred daN when the pressure is equal to 5 bars. Given that the maximum pressure can reach 20 bars (maximum pressure admissible by the yarns), one can realise the strength abilities of these structures: they can support up to a hundred times their own weight.

Inflated tubes

Tubes are also made of coated and prestressed linen cloths.

Bending shape

Many tubes have been tested with diameters varying from 60 to 180 mm. They are also simply supported "beam" loaded by a concentrated force and the length between the supports is about

2 m. The inflation pressure will vary up to 4 bars. The bending shape of a tube with ϕ 156 and a pressure of 2 bars is shown Fig. 3.

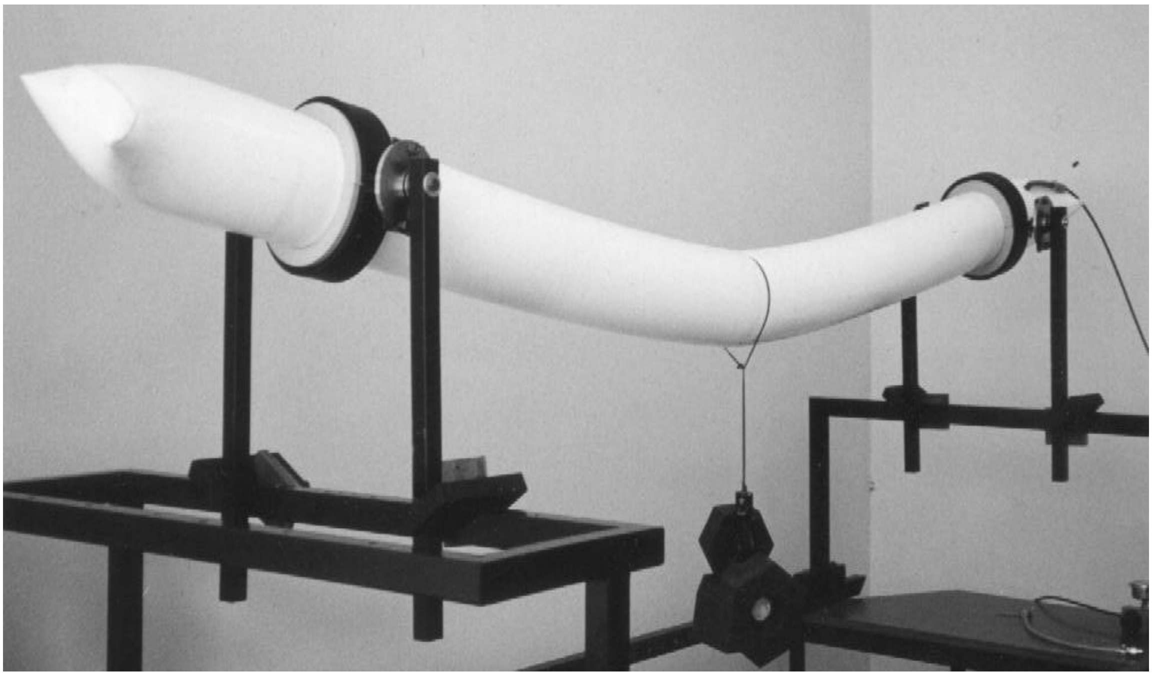

Fig. 3 : bending shape of the tube

One can see that the bending shape is one ever quasi linear between points of loading. The free ends are here straight but don't remain horizontal. Once again light curvatures appear near the loading point. The tubes have also a tight yarn behaviour between points of loading and not a beam behaviour.

Limit load

We will define the wrinkling load F_W as the value of the load which gives a local buckling of the upper part of the tube (when wrinkles appear). This load is once again a linear function of the applied pressure. The wrinkling load results for three of these tubes is given Table 2.

Table 2 : Experimental wrinkling load as a function of the pressure for the tubes

	p (bar)	1	2	3
F_w (daN)	ϕ 120	6.6	12.8	17.6
	ϕ 156	14.6	28.1	38.8
	ϕ 180	24.1	47.7	65.

In fact the tubes can support greater loads, because parts of the tubular section can have zero stresses before reaching the collapse load. This limit load is about 1.8 times the wrinkling load. For instance, the bigger tube collapses at 120 daN. One can realise here again the strength abilities of these tubes: they can also support a hundred times their own weight. Another remarkable property of these structures is that "shakedown is reversible": after loading the panel or the tube up to its limit load and unloading, it comes back to its initial shape without any damage.

SIMPLIFIED THEORETICAL MODELS

Results on the deflection.

Given that the shape of the deformed structures is linear between points of loading one can try to use a tight yarn model. It's obvious to show that the yarn theory gives respectively for the panels and for the tubes :

$$v = \frac{F\,l}{2\,p\,b\,h} \qquad \text{or} \qquad v = \frac{F\,l}{2\,p\,\pi R^2} \tag{1}$$

where p is the pressure, b the width, h the height of the panel, R the radius of the tube, and l the half length between the supports.

Unfortunately, a comparison between experimental and theoretical results shows that the yarn model gives valuable results on the deflection when the pressure is low, but the results are very bad for higher values of this pressure. Tables 3 and 4 give a comparison of these values for a panel and for a tube.

Table 3: experimental and tight yarn model deflections for the panel

p (bar)	0.5	1	2	3
F (daN)	12	18	30	40
Exp (cm)	4	5.2	8	9
Yarn (cm)	3.8	2.9	2.4	2.1

Table4: experimental and tight yarn model deflections for the tube ϕ 156

p (bar)	1	2	3	4
F (daN)	12	25	35	45
Exp (cm)	6	9	10	12
Yarn (cm)	3.2	3.3	3.1	3

One can see that when the pressure reaches 3 or 4 bars, yarn theory gives deflections four times lower than experimental ones. A beam model have been developed by Main & al [1] and they have shown that inflated tubes behave like beams, which is true because their study has been done with tubes submitted to 0.35 and 0.7 bar.

This beam model can't be used here, because in a beam theory, the deflection is independent of the pressure, which is not the case here as shown in Table 5. Moreover it's impossible to relate the bending momentum to the curvature of the beam: the first is linear between points of loading and the second is zero! We can't therefore define a flexural rigidity.

Table5: experimental deflection for a given load

p (bar)	1	2	3	4	5
v (cm)	6.3	4.2	3.5	3.2	3

Limit load.

A beam model can be used to calculate the limit load of these fabric structures because the yield mechanisms of beams satisfy linearity between plastic hinges. One can show [1] that the theoretical limit load for a panel is given by:

$$ {}_{l} = \frac{p\,b\ \ {}^{2}}{l} \qquad (2)$$

where p is the pressure, b the width, h the height and l the half length between supports. For a tube the wrinkling load is be obtained when the stress vanishes on the upper part of the tube [5], which leads to:

$$ F_W = \frac{\pi\, p\, R^3}{l} \qquad (3)$$

Theoretical values of these loads are close to experimental results and are obtained within 20% error as shown in Tables 6 and 7.

Table 6: Theoretical and experimental limit loads for the panel

p (bar)	1	2	3	4
Ex load (daN)	9	19	28	38
Th load (daN)	7.8	15.6	23.4	31.2

Table 7: Theoretical and experimental wrinkling loads for a tube

p (bar)	1	2	3
Ex load (daN)	14.6	28.1	38.8
Th load (daN)	15	30	45

These results are very interesting because they show that the limit load is proportional to h^2.for a panel and to R^3 for a tube. Given that the weaving process of the cross section for a panel can give heights up to 20 cm, and that it's not difficult to find fabric tubes with radius up to 15 cm, we can assert that thick inflated fabric beams have very good strength abilities. For instance, a "bridge" with 4 m width, 20 cm heights, 20 m length built with one of these panels submitted to a pressure of 10 bars, can support a light vehicle which can take away the bridge after crossing! This same bridge can be built with several tubes.

NUMERICAL MODELLING

In order to obtain results on the deflection and to refine the values of the collapse load, we have solved these problems by the finite element method. The panels were studied on the assumption that cloths are membranes in tension, that the connecting yarns are non linear bars and that the pressure can be replaced by following forces applied normally to the cloths. A special finite tube element submitted to internal pressure has been used for the modelling of the tubes. The problems were studied with the hypothesis of large displacements and with following forces. The constitutive law was obtained from experimental data on the fabrics.
The equations of this kind of problems and their discretized form leads to solve the following incremental system [6] :

$$(K_1 + K_2 - K_3)\, \Delta U \;=\; P - R \qquad (4)$$

where K_1 is the classical stiffness matrix, K_2 is the non linear geometrical matrix, K_3 is the non symmetric matrix providing from following forces. ΔU is the vector of incremental displacements, P is the vector of external loads and R is the vector of internal or resisting forces. All computations have been done with Castem 2000 [4].
Numerical results concerning the deflections as well as the limit loads of the panels are very close to experimental ones and can be found in Wielgosz & al [3]. A comparison between theoretical and experimental values of the deflection for the tube ϕ 180 is shown Fig. 4. Theoretical values are obtained with 15% error, which is not so bad given that they are the unique results which can be found for this kind of structures. A 3D analysis with shell elements is in progress. These computations are essential to refine the values of the collapse loads of the tubes.

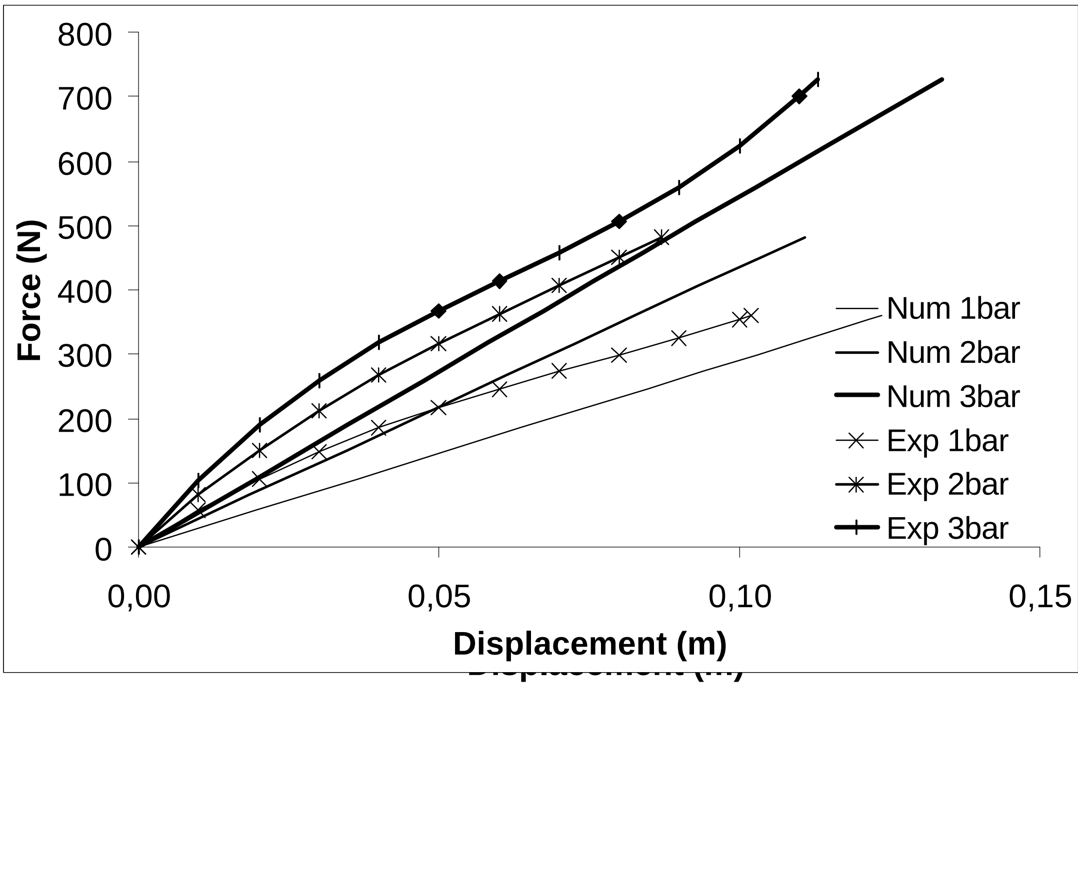

Fig. 4 : theoretical and experimental values of the deflection

CONCLUSION

These first experimental and numerical results on the modelling of the behaviour of fabric beams at medium pressures show that it is now possible to compute this kind of inflated structures and therefore to foresee the building of light, easily transportable and extremely strong fabric structures. Their industrial application can be very numerous: crossing structures, provisional buildings, light roofs,.... One have now to work on the reliability of such structures in order to prove that they can be used by industry.

REFERENCES

1. J. A. Main, S. W. Peterson, A. M. Strauss, “Load - deflexion behaviour of space - based inflatable fabric beams”, *A.I.A.A. Journal* , 1994, Vol 7, N° 2, pp 225-238.

2. C. Wielgosz, E. Leflaive, J.F. Dubé, “Etude expérimentale et modélisation numérique d'une structure panneau gonflable”, *Troisième Colloque National de Calcul des Structures,* Giens, 21-25 Mai, 1997, Vol 1, Presses Academiques de l'Ouest, Eds, pp 151-156.

3. C. Wielgosz, E. Leflaive, J.F. Dubé, “Experimental study and numerical modelling of inflated fabric panels”,*Computer Methods in Composite Materials VI,* S.V. Hoa, W. P. De Wilde, W. R. Blain, Eds, Computational Mechanics Publications, 1998, pp 137-145.

4. CASTEM 2000, Guide d'utilisation de Castem 2000, version 96, 1996.

5. R. L. Comer, S. Levy, “Deflexions of an inflated circular cylindrical cantilever beam”, *A.I.A.A. Journal* , 1963, Vol 1, N° 7, pp 1652-1655.

6. P. S. Han, M. D. Olson, “Interactive analysis of wind-loaded pneumatic membrane structures”, *Computers & Structures*, 1987, Vol 25, n° 5, pp 699-712.