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# Conclusions and Suggestions for future works

In the present work membrane structures more precisely pneumatic structures for constructions in civil engineering are studied. This type of construction is quite new and requires new technologies. Therefore, new materials are under development. Due to the large amount of materials available for membranes such as fabrics and polymers, different material models are adopted. The material models are classified here in two main groups: small and large strains. In the group of small strains elastoplastic and elastoviscoplastic material models were implemented. The group of large strains comprehend the implementation of the hyperelastic Ogden, elastoplastic and elastoviscoplastic material models. A new material model is also proposed and implemented, which is based on NURBS surfaces. Examples are developed to validate the material and implementation.

Emphasis is given to the ETFE material due to its wide use in pneumatic structures in the last years. The constructions built with ETFE materials show the efficiency of this material. Numerical analysis with the finite element method are applied to model the ETFE material.

The pressure–volume coupling included in the formulation takes into account the variation of the internal pressure in enclosed chambers when the volume is changed due to the external applied load. Numerical results are compared with analytical results available in the literature. An analytical formulation for large strains is also developed.

Applications of the material models to membranes and pressure–volume coupling are performed in the present work. The tools developed in the work are applied to the analysis of a structure in use.

## 7.1
## Membrane material models

The elastoplastic material models for small and large strains are considered in the numerical models of uniaxial and biaxial tests of ETFE–foils. The experimental results for the biaxial tests for load ratios of 1:1 and 2:1 are compared with the numerical models. Membrane structures clearly present large deformations by which the small strain material model fails to give good results. Experimental results validate the implementation and applicability of the large strain models.

The proposed material model based on NURBS (PD–NURBS) was validated with examples for hyperelastic and elastoplastic material models with large strains.

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From the small error obtained with the results comparing the PD–NURBS material and the conventional material models it can be concluded that the formulation presented is in accordance with the results of conventional models.

The validation example of the perforated square membrane with Mooney–Rivlin material model are compared with the variation of the number of control points for the material model based on NURBS. The results obtained with the different nets of control points are compared with the global convergence of the numerical models. From the results it is concluded that as the number of control points increases the convergence rate also increases and reaches quadratic convergence.

The material behavior is defined with NURBS surfaces with stresses and strains in principal directions. These NURBS surfaces are generated with the results from biaxial tests. The advantage of this material model is that from results of experimental tests, a material model can describe the material behavior. On the other hand, the experimental data should provide a point distribution to generate good NURBS surfaces. This point distribution could result in a necessity of a large range of experimental data.

With respect to time of the analysis no significant difference between the PD–NURBS material and conventional material was observed.

We conclude that this material model is a good alternative to conventional material models.

The burst test of a circular membrane clamped at its rim is analyzed. This test is modeled with finite elements and the numerical models are compared to experimental results. The elastoplastic material model with von Mises yield criteria is considered in the numerical analysis for small and large strains.

The results obtained with the numerical analysis with large strains are in accordance with the experimental results. On the other hand the results of the numerical analysis with small strains are valid only in the first steps of the analysis. These results reinforce the importance of considering a material model with large strains to model this type of material.

## 7.2
## Pneumatic structures with pressure–volume coupling

The numerical implementation of pressure–volume coupling for pneumatic structures was validated with analytical analysis. The analytical analysis in the literature are for an inflated circular membrane clamped at its rim. Difference was observed between the numerical and analytical results and this was accredited to large strains, which were not considered in the analytical solution available in the literature. This was confirmed with the development in the present work of

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an analytical solution with large strain kinematics. The results obtained with this analytical solution were the same as those obtained with the numerical analysis.

A rectangular inflated cushion of single and double chamber is modeled in the present work. The results obtained for the case of pressure–volume coupling and without considering the pressure–volume coupling are compared.

For the double chamber cushion with pressure–volume coupling it is observed that the displacement result is smaller than the cushion of single chamber, due to the increase in the displacement constraint with the increased chamber.

These analyses show the large difference in the results when the pressure–volume coupling is considered.

An analysis of a pneumatic structure in use is also performed in the present work. The importance of the pressure–volume coupling is reinforced with this example by the results of displacement, stresses and strains. The results obtained for the cases without the pressure–volume coupling are larger than the cases with pressure–volume coupling.

The analysis with cutting pattern shows the accumulation of the tension on the strip unions. Therefore, the cutting patterns should be considered in an analysis of a membrane structure.

## 7.3
## Suggestions for future works

Based on the present work some suggestions for future works are presented:

- Experimental tests for isotropic membrane materials for different stress paths should be performed to generate NURBS surfaces for the constitutive material model based on NURBS.
- Extension of the formulation of the material model based on NURBS to anisotropic materials.
- Consideration of the temperature influence on the material model for pneumatic structures.
- Development of experimental analysis of inflated cushions with multi chambers, since these experimental analyses are not available in the literature.
- Wrinkling analysis in pneumatic structures
- Dynamic analysis in pneumatic structures

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