NON-LINEAR ANALYSIS OF ORTHOTROPIC MEMBRANES

Análisis no-lineal de membranas ortotropicas

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This paper presents the initial activities of an ongoing research on the analysis of orthotropic membranes, considering geometrical nonlinearity. The subject is relevant for the consistent description of the materials used in the production of the current structural membranes and for the proper consideration of wrinkling in such type of structures. The paper will briefly display some of the theories available to describe the wrinkling phenomenon as well as some of the typical failures related to it. The work also outlines the phases of the production and the associated inspection procedures and emphasizes the importance of experimental studies. Possible applications of our analytical studies are presented.
Key words: membrane, shells, finite elements, wrinkling, orthotropic materials, nonlinear analysis.

INTRODUCTION

According to Billington (1983) a structure can be considered in three different dimensions: the scientific, the social and the symbolic ones. The scientific dimension, measured by efficiency, essentially means building with a minimum of material and yet enough strength and durability. The social one, which comprises mainly the cost analysis with respect to the usefulness of the design, is measured by economy. Finally, the symbolic one encompassesthe aesthetical issues,i.e. how elegance can be achieved within the constraintsset up by the scientific and social criteria.There is a constant search for buildingsthat improve these three dimensions at the same time,and tension structures are anexcellent way to do so (see figures 1 and 2). It is not by chance, therefore, that tensionstructures are more and more being constructed all around the world, and that research on this field are motivating and sometimes, even enchanting. Membran estructures adjust load conditions undergoing large displacements,thusinducing severalgeometric nonlinear effects. The mechanical behavior of membranes in architecture, civiland aeronautical engineering is already widelyrecognized.Besides structures, it is also important, for instance, in biological systemslike the human body – veins, heart and specially the skin.The wrinkling ofmembranes has been a research topic of continuous interest, because it affects quality, performance, appearance and safety of the membrane structures. Wrinkles can be material, representing permanent deformations due to manufacturing and wrapping, or structural, dueto the installed stress field. At present, much research is spent on finding apractical representation of this phenomenon.

We expect to show, in this paper, the importance of our future work. In most analysis, e.g. (Mansson, J., Söderqvist, J., 2003), the bending stiffness of the membranes has not been properly considered, leading to unsatisfactory results in the modeling of wrinkling. It seems therefore very interesting to apply a complete shell theory to describe the wrinkling phenomenon, in the lines of (Flores and Oñate, 2004) and (Cirak and Ortiz, 2001). As a first step in a broader numerical research to be pursued on the wrinkling phenomenon, we describe in this paper some modes of failures due to wrinkles, in order to motivate our research. We go further by discussing the importance of experimental analysis of the fabric constitutive behaviour and finally we demonstrate our objectives and expectations.

Fig. 1: The first extension of the park of expositions of Bordeaux-Lake (Société Bordelaise D'architecture, 1990)

Fig. 2: A large membrane roof for the Baptist Church of Fortaleza (Pauletti et al., 2003)

WRINKLING

Existent theories

Since the last century, some different theories have tried to describe the structural behaviour of wrinkled membranes. The Tension Field Theory was introduced by H. Wagner in 1929 and was generalized by (Reissner, 1939). It considers that at the wrinkles longitudinal direction exists a nonzero and positive principal stress, whereas perpendicular to the wrinkles there is a null stress. Since wrinkling occurs only at restricted areas of a membrane, (Stein et al., 1961) have introduced a concept of a variable Poisson's ratio that allows over-contraction in the null-stress direction. The relaxed energy density, (Pipkin, 1986), represents the average energy per unit initial area over a region containing many wrinkles. (Roddeman et al., 1987) presented a model that employed a modified deformation tensor expressed in the current membrane configuration. However, since membrane theories and finite elements referred to a current configuration can be very complicated, (Schoop et al., 2002), based in the Roddeman's approach, have worked at the initial reference configuration. On the other hand, (Hornig et al., 2004) introduces an elastic-plastic-type model to improve the description of the wrinkling phenomenon. Still other theories can be found in our references - (Epstein et al., 2001), (Reese et al., 2001), (Tegeler et al., 2003) - or in the literature. One approach often used by tension structures designers to solve the system of nonlinear equations is the dynamic relaxation method, in which the static solution may be regarded as the asymptotic equilibrium state of damped structural vibrations excited by the sudden application of the static load. However (Stanuszek, 2003) has shown that this technique requires an empirical specification of the fictitious mass and damping matrices by the designer, a major inconvenience. Additionally, it is pointed out in that paper that the dynamic relaxation technique is not very effective in case of nonconservative loading or wrinkling. In view of this discussion, we are going to employ the classic methods of nonlinear analysis, as the Newton and the arc-length methods, combined with well established solvers as the sparse Crout algorithm or the pre-conditioned (bi)- conjugate gradient method.

Causes to wrinkles in membranes

We cite in the following some possible causes to membrane wrinkling.

> I. Manufacturing errors: this type of failure is caused by the cutting pattern during membrane production. Wrinkles can appear because the process of patterning is inevitably approximated, but this type of wrinkle can usually be mitigated by proper design of the patterns.
>
> II. Installation errors: these occur especially when there is not a proper control about the applied loads on the structure.
>
> III. Torsion of a fabric panel: in (Miyamura, 2000), for example, analysis and experiments are made for a stretched circular membrane that undergoes wrinkling due to torsion in plane.
>
> IV. Uniaxial loads: the designers try to ensure that warp and weft loads are similar throughout the structure, but this is not always possible, especially near fittings, concentrated loads and edges. This also can be mitigated by proper design.
>
> V. Degradation of fabric mechanics properties along the years, owing to physical-chemical attacks on the material.
>
> VI. Stress relaxation effects; can be mitigated by proper analysis.

MOTIVATION

In tension structures, as conceived by architects, wrinkling is considered a project failure, either of aesthetical or structural nature. From a point of view of the membrane performance, wrinkles can contribute, for example, for snow or rain accumulation, possibly leading to structural failure due to overload. They also generate a new distribution of loads that was not initially foreseen. In addition, as (Pauletti, 2003) comments, wrinkles could be acceptable within certain limits, and for exceptional load cases (like wind pressure loads), but a commercial tool to properly cope with the wrinkled conditions is still not readily available. One should avoid wrinkles also due to aesthetic requirements. But it should also be recognized that wrinkles are more visible to engineers than to the lay people, since the beauty and visual impact of the overall structure may distract the view from local wrinkles. We could even consider wrinkles as desirable, seeing them as a result from the visionary ideas of architects and designers, for, according to (Stroeter, 1989), "the ugly, while grotesque, makes a part of the beautiful; or the beauty is present either in the wealth of shapes or in the daring and innovating solutions that show the courage of who propose it". Anyway, be it to avoid or to provoke them, the analysis of wrinkling of membranes should be possible at the early stages of the design, helping engineers and architects to conceive membrane structures with deeper levels of insight. This is the principal motivation to our present research.

Other areas

Medicine is concerned with the representation of wrinkles, at least in certain cases. (Roddeman et al., 1987) have studied the force transmission from muscle to bone near the elbow joint. They have showed that wrinkling has much influence on the stress state and the force transmission between the tissue structures connecting muscles to bones. The mechanics of scars was considered by (Cerda, 2004). Numerical simulations on elastic membranes can surely help to predict how the skin is deformed after a given suture (see figure 3). Such a tool could allow surgeons to choose between different surgical techniques, a problem that is currently solved solely by the experience of the doctor. Also in fashion design, wrinkles can be undesirable, but could also give life to clothes. Anyway, stylists wood benefit from a tool to represent them. There are works, as for example (Hadap et al., 1999), where purely geometric methods are developed in order to represent cloth wrinkles. But it turned out to be difficult to model the frictional forces that arise between body and cloth, which are important to adequately represent the phenomenon. It is difficult and expensive to erect large structural systems. Inflatable structures are a potential solution, because they are light and can be folded to compact sizes, thus facilitating transportation and possibly materials costs. Compactness and lightness becomes a premium especially in aerospace structures, such as satellite reflectors and communication antennas, systems whose efficiency depends on the removal of wrinkles. Indeed, the aerospace industry is one of most interested sector in a good mechanical description of the wrinkling phenomenon.

Fig. 3: A superficial cut in the skin produces the characteristic thickening, contraction and wrinkling of the skin. (Cerda, 2004)

MATERIAL INSPECTION

The fabric companies are at the beginning of the tension structures production chain. To avoid manufacturing errors, a good inspection process is important. Mehler Haku, for example, a widespread industry that has more than 60 years of experience in fabric development and production, inspects its material in all the stages of production, listed bellow (see also figs. 4 and 5):

PROCESS	INSPECT THE FOLLOWING:
Warping + beaming	Titre (dtex) of the yarn Tensile, number of threads
Looming Weaving Fabric Inspection	Maintenance Heddles and Reeds Weave-Pattern Maintenance of the Loom, Tension Warp and Weft Weaving Faults, Greases, Length
Coating Pass 1 (adhesion layer)	Adhesive of Paste 1, Temperature and Speed of Coating Machine
Coating Pass 2 (main coat)	Thermostability, Colour of Paste 2 Temperature and Speed of Coating Machine
Lacquer Pass 1 (Primer)	Viscosity of Lacquer 1 Temperature and Speed of Lacquering Machine
Lacquer Pass 2 (PDVF top-coat)	Viscosity of Lacquer 2 Temperature and Speed of Lacquering Machine
Master Rolling Edge Cut	Lay Flat Width
Laboratory Tests	Matching with Issued Datasheet
Inspection + Marking Faults	Visual on Faults
Unrolling Labeling	Length Correctness of its Info
Packing	Tightness

Tabla 1: Material Flow and Inspection of VALMEX Structure Material (Mehler Haku GmbH)

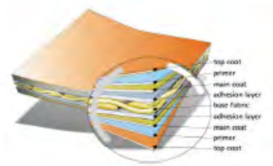

Fig 4: PVC-coated Polyester Fabric (Mehler Haku GmbH)

Fig 5: Weaving – schematic (Mehler Haku GmbH)

THE BEHAVIOUR OF FABRICS

According to ideas in (Houtman et al., 2000), the textile materials required by membrane structures are made with a woven structural fabric, such as cotton fiber (organic), nylon, polyester, glass fiber or aramid fiber, covered with PVC, Teflon, or silicone films in one or both sides to provide water tightness and protect them from pollutants. The choice of the fabric configuration depends on several factors: durability, cost, desired translucency, and resistance to environmental actions, high temperatures, stretching, perforation and the action of the UV rays. Many studies consider the membrane material like homogeneous,isotropic and without mass.These hypotheses are not strictly realistic, since real materials are pretty much orthotropic (see figure 6). The membrane, obviously, has some mass in general and its material is heterogeneous.

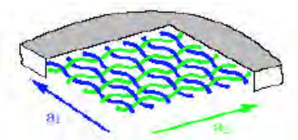

Fig. 6: Orthotropy of the fabrics (Tegeler et al., 2003).

According to (Happold, 1994), for the dimensional stability it is desirable that a fabric has the most possible isotropic behavior and presents a high elasticity modulus. A fabric will never be isotropic due its very nature. He probably meant that a fabric should present similar elasticity moduli on both principal orthotropic directions. However, such fabrics propagate more easily rips in comparison to textiles that present different moduli and are more flexible.

THE IMPORTANCE OF EXPERIMENTAL STUDIES

Researches in the area of tension structures are concentrated in computational modeling and in tests of materials (see figure 7), for instance, (Bridgens et al., 2004) and (Alvim, 2004), usually without performing physical tests on real scale structures. The use of computer programs offers considerable economy compared to physical models. Solutions are achieved faster, and several different conceptions can be tested at more ease. However, experiments stimulate intuition and, according to (Jenkins et al., 1991), material and load characterization, verification of the model and its range of application, determination of the structural properties. Throughout the use of digital photogrammetry, (Grundig et al., 1995) seek compare specified design strains and those existing in an actual textile structure, as well as to perform long term monitoring of membrane strains, in order to investigate creep effects. (Messinger et al., 2003) designed and constructed an apparatus (see figure 8) aiming to understand the mechanical behavior of nonlinear anisotropic fabrics under tension to create new membrane structures. (Titotto, 2003) constructed a similar apparatus in the context of formal aesthetic investigations. It is important to emphasize that it is common to find out papers reporting the calibration of new software against the result of other ones. Even thou this fact does alone not compromise the merits of the new software, it is also quite evident that proper calibration is only guaranteed after independent confrontation with empirical results.

Fig. 7: Biaxial test rig (Bridgens et al., 2004)

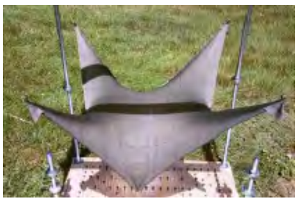

Fig. 8: Apparatus with fabric attached (Messinger et al., 2001).

OUR FUTURE STUDIES

In (Pimenta et al., 2004A) a shell model was developed (in the context of finite elasticity) that is reasonably simple (see figure 9) and fully nonlinear, and with plane stress condition and thickness changes being properly considered. We propose to continue our studies on the phenomenon of wrinkling using this shell model, focusing in the follow objectives:

I. Achievement of a better description of the heterogeneity of the material, considering orthotropic symmetries for the fabric's warp and weft directions, superimposed with isotropic symmetries for the coating polymer materials;
II. Implementation of a proper theory to represent wrinkling;
III. Analysis of inflatable structures, and other structures where wrinkling is relevant.

We have already showed in this paper the importance of describing the wrinkling for some academic areas and applications. Recent studies, as in (Flores et al., 2004) and (Cirak et al., 2001), have shown that bending effects must be considered. (Cirak et al., 2001) comment that under static conditions the mechanics of the inflation of an inextensible airbag may be understood as a competition between the applied pressure potential energy (which is proportional to the volume of the bag), and that due to bending. The former strives to maximize the volume enclosed by the airbag, initially null, and thus favors a finer folding, while the latter strives to minimize the number of folds presented by the deflection pattern. One knows however that, in nonlinear finite elements analysis, the solution convergence is not absolutely guaranteed, and most of the time wrinkling analyses within the field of shell theories are expensive, because the required mesh density is inversely proportional to size expected for the wrinkles. We expect our shell model to overcome at least part of these problems. Moreover, (Hornig et al., 2004) comment about the need to consider the inelastic effects presented by the modern materials applied in membrane structures. In this context, the ideas of (Pimenta et al., 2004B), for the case of elastoplastic shells, can possibly contribute.

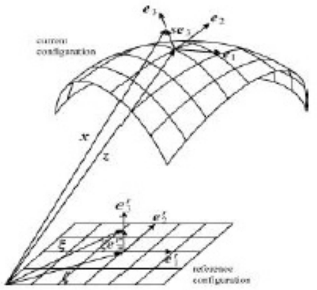

Fig. 9: Shell description and basic kinematical quantities (Pimenta et al., 2004A)

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