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Conference Paper · December 2004

DOI: 10.13140/2.1.3284.2567

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LIGHTWEIGHT STRUCTURES in CIVIL ENGINEERING
INTERNATIONAL SEMINAR of IASS POLISH CHAPTER
Organized by Polish Chapter of
International Association for Shell and Spatial Structures
Warsaw-Częstochowa, 3 December, 2004

The paper was reviewed by two members of Scientific Committee and accepted to printing by prof. dr hab. eng. J.B. Obrębski & prof. dr hab eng. W. Przybyło

ON ASPECTS OF TENSILE STRUCTURES ANALYSIS

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ABSTRACT: This paper describes the numerical aspects of analysis of tensile structures including three principal types: membranes, cable-nets, pneumatic structures and combination of each other. In the first part, the base division and the survey of the form with examples are given. A brief historical perspective and development has been included too. In the next chapter of the article the problems of design and numerical analysis are presented. In the compact form the authors pay attention to the: shaping and form finding, selection of pretension forces in the initial configuration, the choice of constitutive models, the influence of boundary conditions and dynamic wind loads, the numerical tools of analysis' selection, the cutting pattern. Generally, these kinds of problems are the most common in the design processing of tension roofs. The note covers a summary discussion on these specify aspects with a lot of references to the literature in these interesting and developing branches of civil engineering.

Key words: tension structures, numerical analysis, constitutive model, coated woven fabric

1. INTRODUCTION

The tension roofs belong to the modern group of constructions, named also as the tensile structures. They are applied for both: seasonal and permanent usage. The development of numerical methods caused the increasing interest in these new and economical constructions, which cover a wide range of applications in challenging and not-typical designing. Their great functionality lays in the possibility of covering large surfaces with relatively small number of supports. These the innovative architectural engineering systems provide designers a variety of aesthetic free and light forms. However, geometrical and often physical nonlinearities leads to many theoretical and numerical problems which are described in the next part of the paper.

Fig.1.German pavilion at the 1967 Montreal Exposition

Fig.2. Olympic stadium roof in Munich

The fundamentals to designing and constructing were laid by the works of F. Otto, (e.g. [5]) at the turn of the 60's and 70's in the XX century. Later popularization of these interesting objects developed designing and construction of the Germany pavilion in the Montreal Expo in the 1967, see Fig.1 (designed by R. Gutbrod and F. Otto) and the Olympic Stadium roof in Munich, see Fig.2 (designed by G. Behnisch and F. Otto, using the computer program created by J. Argyris and K. Linkwitz).

There are many types of tensile structures e.g.: textile membrane roofs (Fig. 3), cable nets (Fig.1), pneumatic structures (air-supported, Fig. 4), and very often they are used in combination, see Fig. 5.

Fig. 3. Grand Canyon Restaurant [8]

Fig. 4. Roof over tennis court

In the tensile structures the membrane is usually made of some kind of technical fabric or other textile materials. Cable nets are often used in combination with textile membranes, when the forces become too big for the membrane alone. The gaps between the crossings of parallel cables can be covered with conventional materials like glass or metal plates. The pneumatic structures are the other variant of light-weight tension roofs. As the name indicates, the supporting medium consists of compressed air or gas.

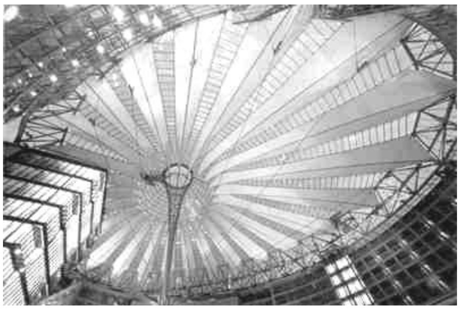

Fig. 5. Sony Center, Berlin

On the other hand we can divide the tension structures on: the framed tension constructions, the custom designed tension roofs, and the rental tents and tent hall constructions. A framed tension structure consists of an internal metal frame and an architectural fabric skin that is stretched over this frame. The internal frame consists of series of arches, purlins, and cable braces. This type of roofing is usually used for ware housings, churches, casinos, and sport objects. Custom designed tension structures (include shopping malls, canopies, sports stadiums, aircraft hangers and ware housings) require the collective efforts of an architect, engineer, fabricator and installer. Rental tents are used to provide shelters for special events such as celebrations and wedding parties. Tent halls are applied for larger gatherings such as hospitality tents for sporting events and exposition halls for trade shows.

2. REVIEW OF ANALYSIS PROBLEM

In this chapter brief characterizations note on the complex problems and critical factors, which exist in the design and construction process of tension structures, have been discussed. Additionally the literature review concerning the mentioned problems has been given.

The first problem is the choice of construction types and shapes. Generally, two principal roof types can be distinguished: supported and tension constructions. In the supported structures the textile fabric is used usually as a roofing material and is fixed principally as a flat fabric covering. Whereas, in the tensioned roofs the negative curvature shapes usually are applied. It guarantees proper pre-tensioning, but also causes some problems with a roof shaping. The following shapes are mainly used: hyper parabolic, saddle, crescent, ridge and valley (see Fig. 6).

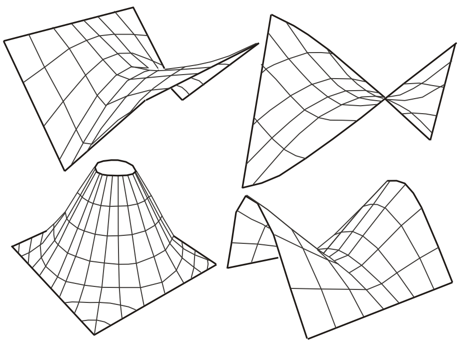

Fig. 6. Typical tension roof shapes

Zalewski and Allen have presented in details the problem of shaping structures in their work [1]. This work includes the step-by-step examples, using both numerical and graphical techniques, of simple but powerful methods for finding form and forces for arched, suspended and cable-strained structures. Lewis et al. in [2] document a computational approach adopted for the form-finding of lightweight tension structures comprising prestressed cable nets and fabric membranes. The approach utilizes the minimum potential energy principle of surface tension for finding optimum shapes of tension membranes. In the report of the American Society of Civil Engineers Task Committee on Tensioned Fabric [3] we may find the primary rule of designing, material choice and details of building process of technical woven fabrics made roofs. Advantages and disadvantages of different methods of the shape determination and its analysis are given too. In the compact form in [4] Berger described the principal structural forms of tensile structures and solutions to special problems related to fabric structures for permanent buildings. It is worth paying attention to a monumental two-volume work [5] by F. Otto, concerning the hanging structures. These books include the history, development, classification and the principles of calculations and designing with a large number of hanging constructions examples. In Poland, at the beginning of 60's of the last century, Krzemiński in [6], as one of the first authors, gave the classification of surfaces used in the shells roofs analysis. He included large number of references and examples of those structures.

The next problem which should be considered is proper choice of materials. For cable structures the selection of material type is relatively easy. The most problems are concerned on the membrane and pneumatic roofs in which the technical woven fabric usually are applied. Detailed information about materials used for membrane structures have been presented e.g. in [7]. Such materials as: cotton fibre, polyamide, polyester, fibreglass, aramid fibre are analysed in this work, also the specific properties are defined and adopted. Finally, the structural behaviour of the fabric is discussed and mechanical properties of common fabrics are given. Increasing interest of these constructions caused the arising of significant number of corporations and firms which are involved into the textile materials distribution and full designs including solution of the construction problems (e.g. FERRARI, see website [8]).

The selection of a constitutive model for a technical fabric is the following important problem concerning materials modelling. Due to discrete microstructure, non-linear and inelastic strain-stress relationships, flexibility, large deflections and rotations, problems dealing with woven fabrics are much more difficult to solve. We can distinguish two main groups of constitutive models: continuum and discrete. In the continuum models, the woven fabric is treated as a continuum without explicit reference to its discrete microstructure. During LSCE04, the authors will present the dense net model. It was described in [9] and developed in [10]. The advantage of this model depends on taking into account the change of the angle between threads families during deformation. However, this approach has also a drawback: the force in a given family of threads depends on the strain in the same direction only. That means that the influence of PVC coating in the forces' distribution is neglected. The application of this model was extended in paper [11] on coating influence. The common coated fabric (Fig. 7) consists of the threads' net, usual two families of fabric named the warp and weft (see Fig. 8), both coated with the material like PVC or PTFE. The covered textile materials have been characterized e.g. by Filipkowski and Jacoszek [12]. In this paper the results of tests in uniaxial and plane stress states are presented as well as data obtained in normal or fully humidity. The compressive analysis concerning the identification of the elastic and viscoplastic material parameter (technical woven fabric "Panama") for the dense net model are described by Kłosowski et al. [13].

In the paper [14] the formulation of continuum constitutive equations for fabric membranes for architecture by Kato et al. was proposed and discussed. The formulation is based on the fabric lattice model where the structure of the fabric membranes is replaced by an equivalent structure composed of truss bars representing yarns and coating material. The equations consider the material nonlinearities of yarns and coating and include crimp interchange between warps and wefts. The pseudo-continuum model is described in [15] by Kuwazuru and Yoshikawa. They proposed the material modelling method, based on the new definition of the strain-displacement relationship for the plain-weave fabric. This model transforms deformations of a fabric into the axial tensile strain and transverse compressive strain, separately for a warp and for a weft. The non-orthogonal constitutive model for characterizing the woven composites is presented in [16]. On the basis of the stress and strain analysis in the orthogonal and non-orthogonal coordinates and the rigid body rotation matrices, the relationships between the stresses and strains in the global coordinates are obtained.

In the discrete model, the woven fabric may be modelled as an assemblage of their constituent fibres. This model by itself has limited possibility to predict complex fabric deformations, due to the prohibitive number of yarns. These types of models are useful for prediction of the fabric mechanical properties from the yarns, because a small patch of cloth needs only to be modelled. In [17], the micro–mechanical model was developed, and then in [18], it was applied for woven fabric composite finite element analysis, based on nonlinear stress–strain relationship. The representative volume cell was divided into many sub-cells and the effective properties were obtained by the homogenisation technique. An interesting approach to the discrete model used for PVC-coated fabric is discussed in [19] by Argyris et al. Various aspects of the constitutive modelling including the novel experimental testing procedures, the identification of rheological parameters for viscoelastic material are presented there. The detailed characterization of the constitutive models, applied to the description of technical woven fabric, is described i.e. by Ambroziak and Kłosowski in [20]. Kazakevièiūtė-Makowska [21] presented the material modelling (stress-strain relations) of fabrics and their role in the design of fabric structures.

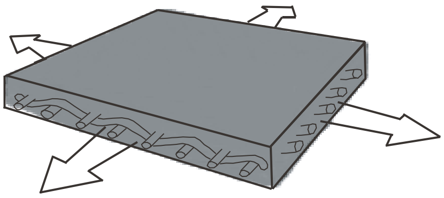

Fig. 7. Visualization of coated technical fabric

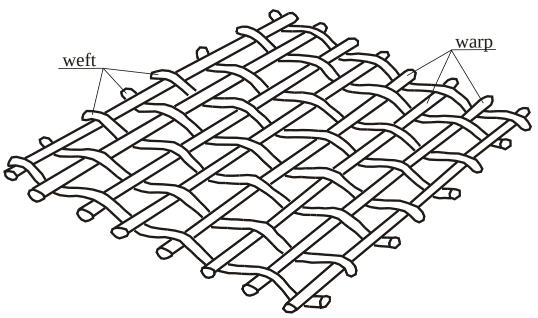

Fig. 8. Threads' net

The operational loads (i.e. wind and snow forces) are the next problem which must be considered. In structures analysis, the snow loads, in general, are not taken into account for seasonal constructions as they are dismantled in winter. In permanent structures the influence of snow loads must be included. If selection of the shape is incorrect or the tension forces are too small, snow bags can appear and damage the structure. The analytical value of these loads depends on climatic zones which are defined in the national standards and the design specifications for each country. On the basis on the Polish standards the authors in the paper [22] proposed the simply conception to acceptance of these kind loads.

The work [23], elaborated by Kazakiewicz et al., describes tunnel tests for many shapes of hanging structures and gives values of reduction coefficient which can be used for practical determination of wind loading for calculation of structures. The two volume engineers' handbooks [24] and [25], written by Cook, concerned on the foundations of the wind loading specification. The books give the practical instruction to these loads values determination. The practical example of a hyperbolic paraboloid hanging roof dynamic calculations is presented by Kłosowski [26]. This paper describes the elementary rules of the wind loading determination and discusses the behaviour of the chosen hanging roofs on the blast of wind loading. The proposed concept of wind loading has been extended by Ambroziak and Kłosowski [27]. In the paper [28] we can find the detailed literature review of the wind loading determining for hanging structures.

The next problem during designing process is the choice of the numerical analysis method. Nowadays, the Finite Element Method (FEM) is the leading approach in constructions analysis. The numerical analysis of large deformations of flexible membrane structures is considered e.g. by Stanuszek [29]. In this paper a concept of taking wrinkles into account based on the cable analogy is presented. The proposed technique was based on the natural approach [30] of the stress–strain state in the element and allows us to find the solutions for even very complex membrane systems with large wrinkled zones. The problem of interaction between a pneumatic structure and the surrounding air using BEM and FEM was analysed by Sygulski [31]. In the next paper [32], Sygulski presented a numerical analysis of membrane stability in air flow. The problem is described by differential and integral equations, and the FEM and BEM are used to solve these equations, respectively. Orkisz [33] at the beginning of the 80´s latest century achieved fully literature review in the field of theory and calculation methods of pneumatic roofs, distinguishing on the basis different schools and gave compact characteristic and indicated the development directions of pneumatic roofs mechanics. Generally, for tensile membrane and pneumatic constructions in the finite element analysis triangle tree-node elements in plane stress state and four-node isoparametric membrane elements [34] are most often used. Consequently, the initial stresses should be included into the stiffness matrix. If isoparametric elements are used, the method of the surface integration must be properly chosen. Also the determination of the angle between threads during deformation process should be discussed. In the dynamic approach, the selection of a time integration algorithm is most important, as in non-linear calculations all direct methods of integration are conditionally stable and the methods based on the modal superposition are ineffective.

The following problem of tension structures is pattering, in which a 3-D (three dimensional) shape is translated into a 2-D cutting pattern. The cutting pattern is a two-dimensional representation of a three dimensional space structure. The determination of a suitable technical fabric cutting pattern is the area most likely to cause difficulties in recreating the geometry of a stable minimal surface. The process concerns the flattening of a segment of the three dimensional form-found surface onto a two dimensional plane, such that the flattened segment fits within the maximum allowable width of the fabric, and the geometry of the 'sewn' structure closely approximates that of the form-found surface. The flutter wind effect generated by wind forces acting on the structure must be considered too. Filipkowski et al. [35] presented practical information concerned the open air theatre in Połczyn Zdrój in Poland. The authors described the behaviour of textile material, roof geometry, construction and execution, erection and pretension of membrane, test results of roof nodal forces.

3. RESEARCH AND DEVELOPMENT SURVEY

The tension structures are the main research subject of a many institutions, i.e. TensiNet [36], International Association for Shell and Spatial Structures (IASS) [37]. TensiNet is a European project funded by the EU Commission. The consortium TensiNet consists of 22 participating organizations with representatives from 9 EU member states. The membership forms a complementary group representing multi-disciplinary industries, universities and other associations. Within the thematic network the partners will make the knowledge of their specific domain available and will exchange and share know-how between different disciplines. TensiNet will assemble structure and analyse existing data and integrate this expertise in knowledge bases. TensiNet is co-ordinated by Vrije Universiteit Brussel (VUB). The International Association for Shell and Spatial Structures was founded in 1959 by Eduardo Torroja and a group of prominent pioneers in the field. The aim of the Association is to facilitate the interchange of ideas related to the design, analysis, construction and research on shell and spatial structures through organizing annual symposia, publication of the IASS Journal, sponsoring activities of a number of Working Groups, and collaborating with other professional and scientific societies. It is worth to pay attention to the Polish Chapter of IASS with a wide range of activity in the many science branches concerned the light weight structures including hanging roofs.

Many of academic institutions make the active investigations concerning the developed of the tension structures, for example: Institute for Membrane and Shell Technologies in Bobingen (Germany)

[38]; Institute for Lightweight Structures (University of Stuttgart, Germany) [39]; Newcastle University (Structural Engineering, United Kingdom) [40]; University of New South Wales (LSRU, Lightweight Structures Research Unit, Australia) [41].

Conferences and symposia organized all over the world show the significant role of the tension structures development. For example in the year 2005 the 2nd International Conferences on Textile Composites and Inflatable Structures, the Structural Membranes [42], and the 5th International Conference on Computation of Shell & Spatial Structures [43] will be organized.

Nowadays, in the period of global web development it is worth to pay attention to the many interesting web sites, for example Arcaro in his work [44] elaborated a web page with information on the design, analysis and interesting references to a lot of articles, audiovisuals, books and software for tension structures calculations.

5. CONCLUSION

Tension structures have been used in many buildings for almost 40 years. Some of these applications are significant for their size. The authors are aware that problems motioned here are widely discussed in the literature, but very often presented results are incomplete or difficult to obtain (technical reports).

During LSCE04 the authors, besides the literature examples, will present their own experience and analysis of the hyper hanging roofs. The chosen shape of the roof for static and dynamic numerical calculations like Grant Canyon Restaurant (Fig. 3) is taken. In the analysis of constructions, which will be presented, the dynamic character of the wind load is considered.

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