THEORY AND DESIGN OF ENVIRONMENTALLY COMPATIBLE LIGHTWEIGHT HYBRID STRUCTURES

Stanislav KMET-Lubica HOLICKOVA-Jan KANOCZ

The Technical University of Košice, Faculty of Civil Engineering, Vysokoskolska 4,
042 00 Kosice, Slovak Republic, Europe
Phone:++421 95 6233 416 E-mail:kmets@ccsun.tuke.sk

INTRODUCTION

The present trends of the modern large-span structures are characterized with introduction of the new types of structural systems with ecological, economical and aesthetical properties with very flexible use for the variable space surfaces and shapes of ground-plans.

By means of purposeful mixing of the different materials (steel, timber, composite materials created of glass fibres or plastics, high-strength fibres and cables etc.) and by means of suitable placement of the elements or subsystems with required material in whole systems , the very effective lightweight hybrid large-span structure are obtained.

Environmentally compatible structure respects the principles of equilibrium and preservation of the environment over a specified period of the time and under specified conditions. Reliability is the probability of a structure performing its function over a specified period of time and under specified conditions. All structural elements, systems and subsystems have certain but different durability within which they perform satisfactorily , but beyond which they can not be used. Interaction between a type of the lightweight hybrid structure and its subsystems and with their elements with global and partial durability is necessary to take into account in the design process. Optimum mixing of the primary and secundary subsystems enables to realize partial reconstruction and recycle the obtained materials. This property is a big advantage of lightweight hybrid structure in comparison with classic constructions.

The durability of primary system is usually longer than is durability of secondary subsystems such as membrane structures etc. It is responsible of the designer to define and determine durability and exploitation period of individual subsystems. The designer-specialist often will have to do some research to get the necessary information for modeling and analysis of the lightweight large-span structures to assess the structural safety and serviceability performance during their construction - assembley, servicelife and possible reconstruction. This approaching requires nonlinear time-dependent analysis of sequentially complexed hybrid structure Fig.1. - Fig.3..

The model presented in the paper can simulate the sequential construction processes of subsystems and elements such as • changes in geometry,• changes in the properties of the materials,• the placement or removal of elements and subsystems,• changes of the prestressing,• stays of prestressing period, various magnitude of prestressing and posttensioning,• the nonlinear time-dependent materials properties,• the structural nonlinear effects of the creep strain increments and deformation.

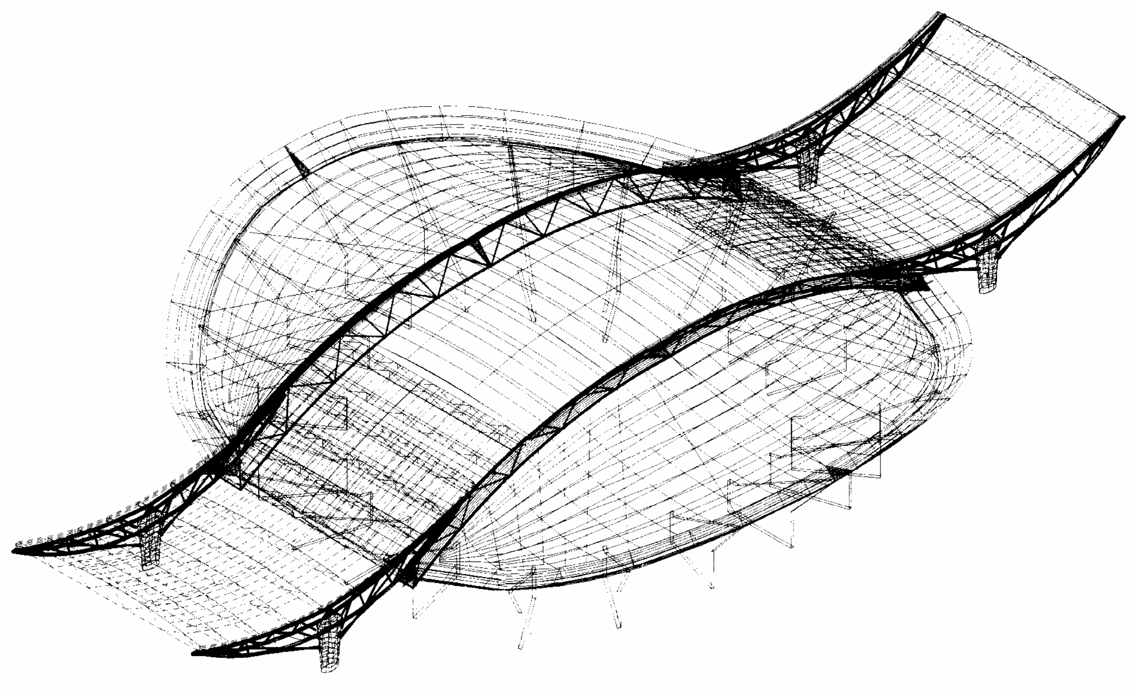

Fig.1. The variant of cable-membrane roofing of the football stadium of the 1.FC in Kosice with retractable segments.

An application of the expert systems to computer aided design and structural engineering in the various areas of design and analysis of lightweight structures allows to simulate more precisely the large group of the time dependence stochastic phenomena which influence not only reliability of structure, but also selection of the economical and optimal design and its required quality.

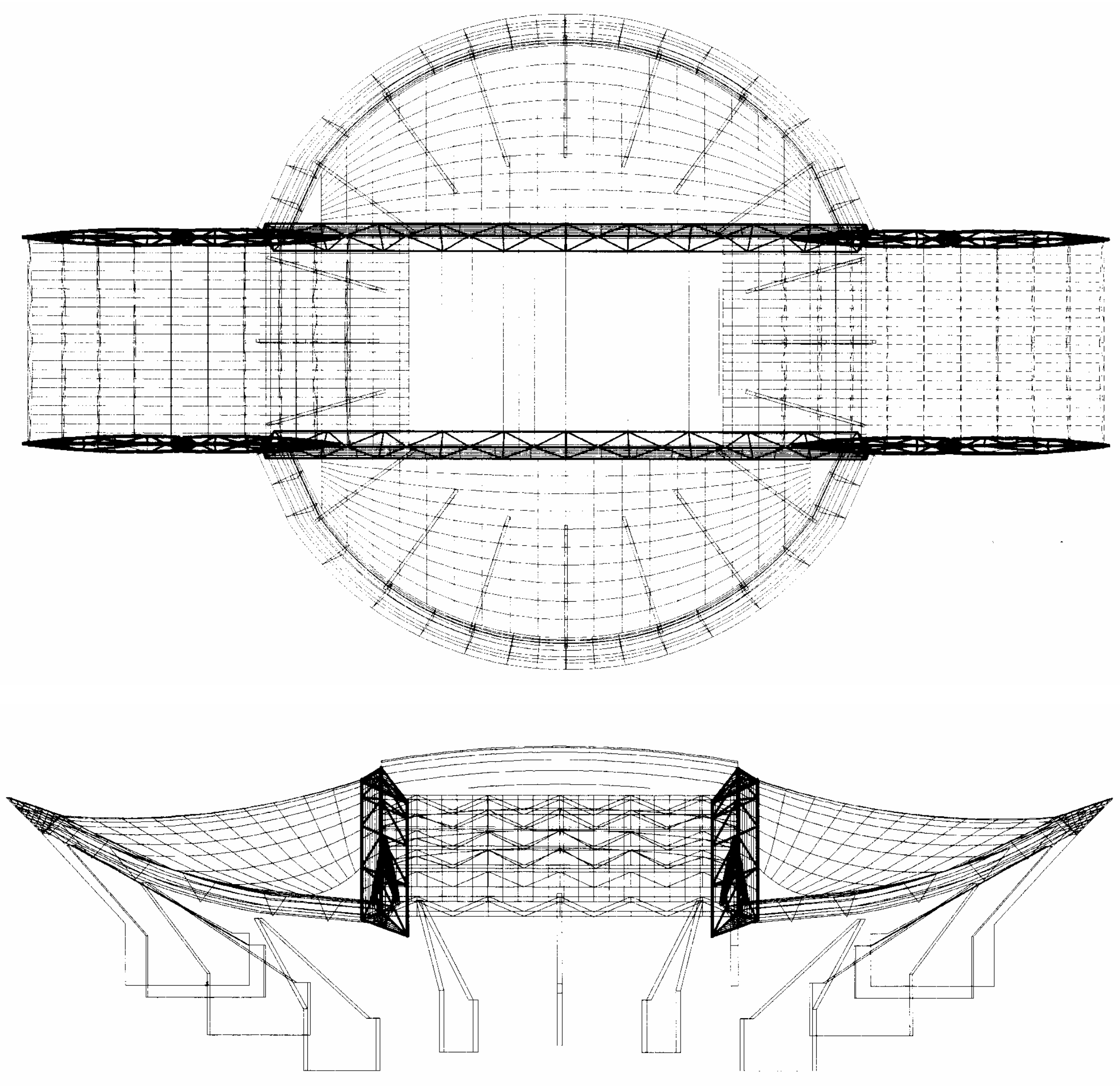

Fig.2. The ground plan and cross section of roofing with retractable segments in the middle of stadium.

NONLINEAR TIME-DEPENDENT ANALYSIS STRATEGY

For the time-dependent analysis of the lightweight structure, the time interval is divided into a discrete number of time steps - time increments. At each time increment the structure is analyzed under the external applied loads and imposed deformations originated during the previous time interval due to creep of cables, temperature variations, decreasing of the prestressing forces, decreasing of modulus of elasticity, etc. In this approach, the initial geometry is taken as the reference configuration.

A stiffness finite element method based on the displacement formulation is used in which the resulting tangential stiffness matrices as well as the equilibrium equations are nonlinear, so as to be valid for current state of material properties and geometry.

Incremental and iterative Newton-Raphson solution strategies have been implemented to solve the nonlinear problem. Within an increment, the geometry and stress update is performed once the iterative process has converged. The convergence is verified with displacements and forces criteria.

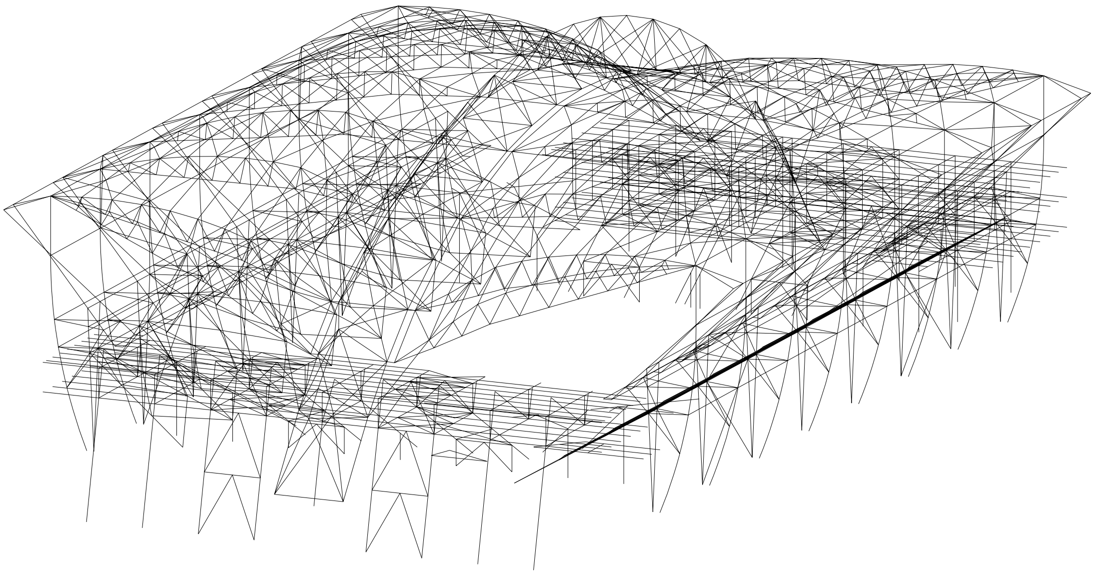

Fig.3. The 3D model of bearing system of the icehockey stadium in Kosice.

The static solution of cable structures can be obtained in studied time t from the system of non-linear equilibrium equations which can be written in the form [2]

$$\left[K_T(t)\right].\left\{W(t)\right\} = \left\{Q(t)\right\} . \qquad (1)$$

The basic equation of the forced vibration at the dynamic analysis has the form

$$\left[M\right]\left\{\ddot{W}\right\} + \left[C\right]\left\{\dot{W}\right\} + \left[K_T\right]\left\{W\right\} = \left\{P(t)\right\} \quad . \qquad (2)$$

The solution scheme can be written as

$$\left[K_T(t)\right]_n = \sum_{i=1}^{N} \left\{\left[K_P(t)\right]_n + \left[K_E(t)\right]_n + \left[K_G(t)\right]_n\right\}_i \ ,$$

$$\left\{W(t)\right\}_{n+1} = \left\{W(t)\right\}_n + \left[K_T(t)\right]_n^{-1} . \left\{\left\{Q(t)\right\} - \left\{R(t)\right\}_n\right\} \ ,$$

$$\left\{F(t)\right\}_{n+1} = \left[K_T(t)\right]_n . \left\{W(t)\right\}_{n+1} \ , \qquad \mathbf{(3)}$$

$$\{X(t)\}_{n+1} = \{X(t_0)\} + \{W(t)\}_{n+1} \ ,$$

$$\{R(t)\}_{n+1} = \sum_{i=1}^{N} \{F_i(t)\}_{n+1} \ ,$$

$$\left| \{Q(t)\} - \{R(t)\}_{n+1} \right| < \varepsilon \ .$$

The symbols in (1), (2) and (3) mean

$[K_T(t)]$ - tangent stiffness matrix of the cable, $[K_P(t)]$ - initial prestressing matrix of a cable structural element, $[K_E(t)]$ - elastic stiffness matrix of a cable structural element, $[K_G(t)]$ - geometric stiffness matrix of a cable structural element, $\{W(t)\}$ - vector of the nodal displacements, $\{X(t)\}_{n+1}$ - vector of the updated nodal coordinates, $\{X(t_0)\}$ - vector of the starting nodal coordinates, $\{F(t)\}$ - vector of the internal nodal forces in each cable structural element, $\{Q(t)\}$ - vector of the external nodal loads, $\{R(t)\}$ - vector of the nodal forces equilibrating the internal forces at node, [M] - matrix of mass of the cable structural element, [C] - matrix of damping of the cable structure, $\{\dot{W}(t)\}$ - unknown speeds of structure, $\{\ddot{W}(t)\}$ - unknown accelerations of structure, $\{P(t)\}$ - in time variable load, e.g. by wind.

The solution of the system of equations is done by means of the Wilson or Newmark method while regarding the specific features and procedures presented in the static solution. Introducing damping into the transformation model is rather demanding and requires many experimental measurements. One of the possibilities is the introduction of Rayleigh′s damping, where on assumption of linear dependence between damping matrix and mass and stiffness matrices , it is possible to determine the damping matrix [C]. This solution requires the knowledge of the logharitmic decrement of the cable structure damping and the knowledge of the first angular frequency which can be obtained by solving the own vibration.

Optimization procedures in the alghoritms of static and dynamic analysis - when solving extensive tasks of finite elements methods and in application of computer engineering it is convenient to form powerful alghoritms with the aim of minimalization of storing the elements of stiffness and mass matrices, or even damping matrices which leads to increase of speed of optimization of structure design. Very efficient is the

SKYLINE method working with a variable length of columns over the main diagonal which is necessary at the triangulation of the matrix.

MODELING OF RHEOLOGIC CABLE BEHAVIOR

Nonlinear time dependent analysis requires accurate simulation of the time-dependent behavior of the cable structural elements. For that purpose , explicit formulations of the constitutive time dependent equations and laws based on the creep tests of the investigated cables were derived. The rheologic effects are defined by nonlinear creep theory as combination of nonlinear elasticity and viscosity.

This model is capable of representing nonlinear time-dependent aspect of cable structural elements such as actual value of cable modulus of elasticity decrease at a studied time due to previous sustained loading.

To study the creep behavior of the singlestrand steel cables, we have selected three test stress levels which enable to apply the nonlinear creep theory for a working up the test results [2].

By the constitutive creep equation in the form of polynomial of third order we know to determine the creep strain increments for an arbitrary stress σ from the experimentally tested stress interval $<\sigma_A,\sigma_C>$.

MODULUS OF ELASTICITY OF CABLE AS A STRESS-STRAIN-TIME FUNCTION UNDER NONLINEAR CREEP

In cable structural elements it is important to apply a suitable way of introducing of the update value of modulus of elasticity into the analysis. We distinguish two stages:

- **The initial stage**

This may be characterized by introducing a constant stabilized modulus of elasticity if the cable structural element passes the process of initial stretching. Further on we can introduce a polylinear stress strain diagram of the cable.

- **Exploitation stage**

Due to long-term load, prestress or overload in certain time interval it may come to strain increments of the cable due to creep $\Delta\varepsilon(t)$ resulting in decrease of modulus of elasticity. On the basis of [1] , we can formulate the relation for modulus of elasticity in the examined time t by means of transformation coefficients and the known course of creep curve in the form

$$E(\sigma,\varepsilon,t)=\frac{\sigma_k-\sigma_{k-1}}{\left[\varepsilon_k(t_0)+\Delta\varepsilon_k(t)\right]-\left[\varepsilon_{k-1}(t_0)+\Delta\varepsilon_{k-1}(t)\right]} \quad . \tag{4}$$

For a stretched cable (Fig.4.) it is possible to accept within the boubdaries of tensile stress σ=<0,05÷0,55>N_r/A_r a linear stress-strain diagram, which can be approximated by the linear analytical function.

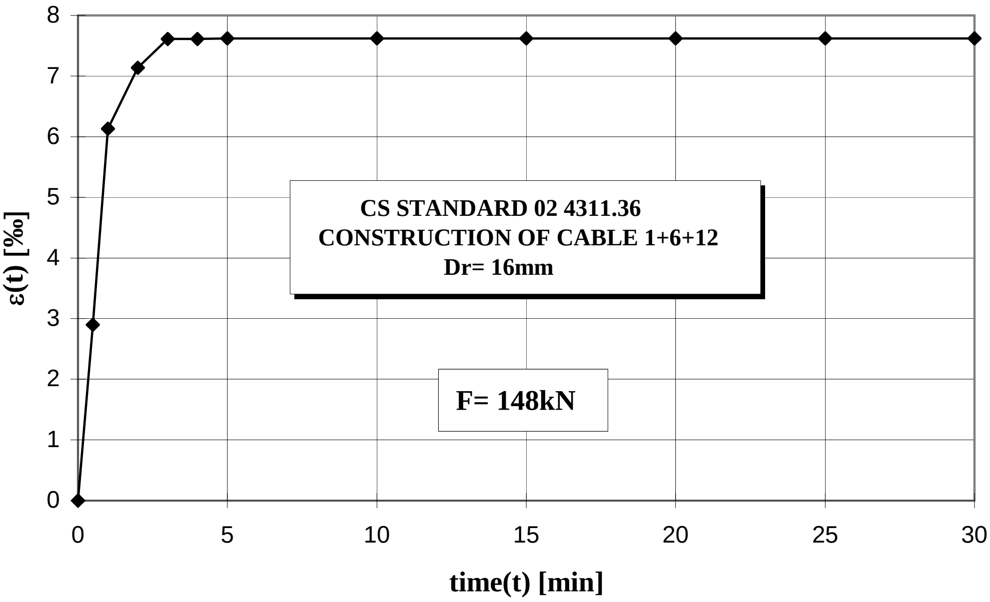

Fig.4. The initial stretching of cable during the time interval 30 minutes.

Then the analytical expression of the actual value of the modulus of elasticity of the initial stretching cable in the studied time is characterized in the form

$$E(\sigma,\varepsilon,t)=\frac{N_r}{2\left[\varepsilon_2(t_0)+\Delta\varepsilon_2(t)\right]A_r} \quad . \tag{5}$$

The decreasing values of the modulus of elasticity caused by creep (Fig.5.) under above mentioned stress levels are in Fig.6.

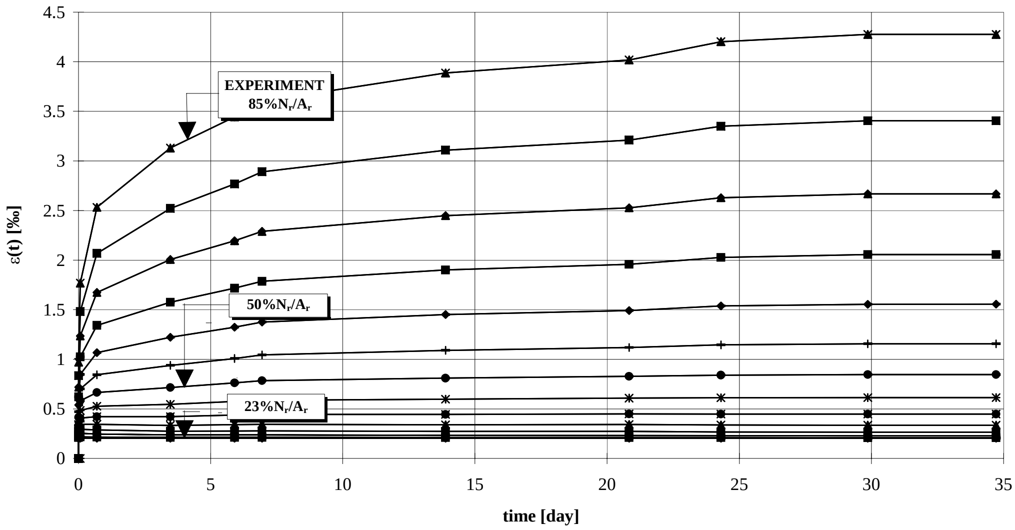

Fig.5.The curves of the creep strain increments of the tested single-strand steel cable.

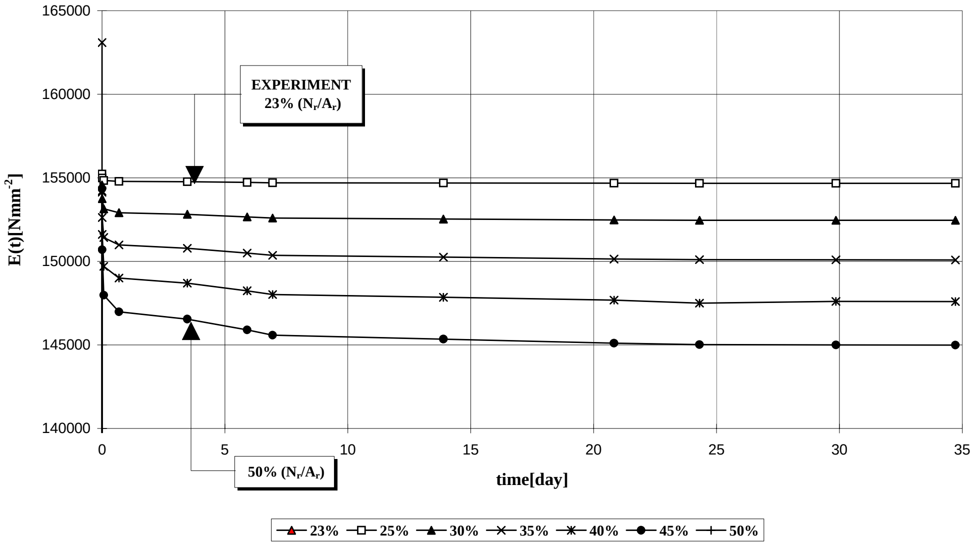

Fig.6. Decrease of the values of the modulus of elasticity of the studied cables.

GEOMETRICALLY NONLINEAR EFFECT AND MODELING OF NONLINEAR CABLE BEHAVIOR

A total Lagrangian formulation is adopted to take into account large displacements which occur in prestressed cable subsystems. The special types of tangential stiffness matrices of cable structural elements as the functions of stress, strain and time were derived.

Young′s modulus of elasticity is in tangential stiffness matrix replaced by the tangent modulus E(σ,ε,t) according to the type of approximation of stress-strain diagram
of cable - polylinear, quadratic or cubic approximation.

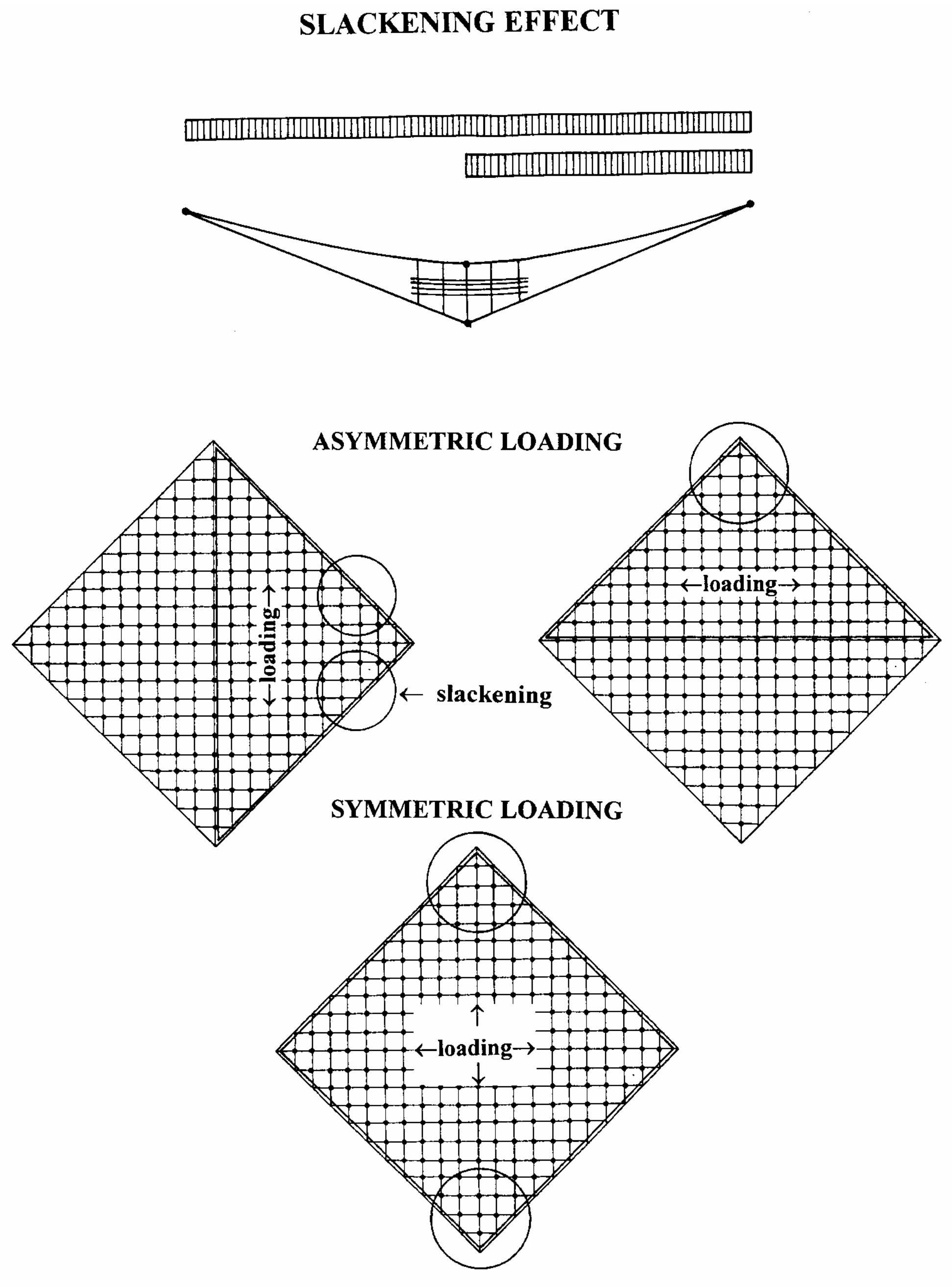

Fig.7. The slackening of the hyperbolic paraboloid cable network.

The effects of nonlinear material properties, including strain reversal and slackening of individual cable structural elements are taken into account, Fig.7. A cable member is considered to be slack when its axial strain $\varepsilon(t)$ in the studied time becomes less than its permanent strain $\varepsilon_p(t_0)$ in the initial time t_0. The axial force of a slack member is set equal to zero and its contribution to the equilibrium equations is neglected.

CONCLUSION

The model developed has been designed to simulate various kinds of structural changes that may occur during the initial and exploitation stage of the lightweight cable hybrid structures. The more accurate qualified transformation model enables the design and solution of large span lightweight cable and hybrid strucures, where the presented static and dynamic analysis provides a more illustrative response of the structure on the acting load. A step-by-step time analysis, consideration of time-dependens effects, the material and geometric nonlinearities together with the consideration of the aspects of initial stretching and prestressing allow one to simulate in a more accurate way most of the actual stiffness and parametric characteristics of hybrid strucure and its structural changes. In such a way, it is possible to find the optimal configuration of geometry, material features and prestress of cables of hybrid structure as well as define durability of the individual subsystems.

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