RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Structural Engineering and Reconstruction

Leonīds PAKRASTIŅŠ

RATIONAL FORM OF HIERARCHIC CABLE STRUCTURES

Civil Engineering, Structural Engineering (P-06)

Summary of Doctoral Dissertation

Supervisor:
Prof., Dr.habil.sc.ing.
K. ROCĒNS

Riga 2004

GENERALDESCRIPTION OF THE THESIS

Topicality of investigation

Weight reduction and increase of spans of structures are topical tendencies in the development of load-bearing structures, which can be accomplished by application of advanced high-strength materials. It is effectively shown as reduction of ratio between the dead and live loads of a structure from ancient massive buildings to contemporary lightweight structures. This ratio can be reduced more times by the exploitation of structural materials with much higher specific strength in combination with structural systems where tensile stresses are dominant in their cross-sections.

Tension structures are characterized by non-linear geometric hardening, which results in a less proportional increase of stress in elements in relation to increased external loads. This provides an increased nominal safety factor evaluated at ultimate limit state of structures. Cable roofs with axially tensioned elements and with identical tensile stresses acting in all the cross-section points represent one type of these structures, and it opens possibilities for rational application of advanced high-strength materials.

The most perspective from the constructional point of view and most expressive regarding architectonical aspect, is a prestressed cable net with negative gauss bending saddle-shaped surface are known as anticlastic form covered with high-strength reinforced foil or fabric. The structure is formed by orthogonally intersected load-bearing concaved and stressing convexed cables. This model is characteristic by kinematic rigidity, and there is no requirement of additional loading for stabilization of structure. The construction has a statically stable shape, preventing such destructive dynamic instabilities, as fluttering or flapping. The model can be constructed on a rectangular supporting contour, which is one of its advantages, and to reach total rigidity of the structure, relatively small radiuses of curvature are needed, enabling to provide the minimum material consumption both of the cable net and its supporting contour. Comparing to different cable structures, deformability under exposure to external loading is relatively smaller.

From the point of view of material consumption (valuable utilization of load-bearing capacity of high-strength materials), the most rational are saddle-shaped roofings with a compliant supporting contour. Rational geometric characteristic values of these roofings with sizes in plan from 10 to 50 m have been determined in a number of the previous works. Functionally the ratio between the roofing volume and the area in larger spans is often unacceptable.

By using the saddle-shaped roofings with a compliant supporting contour as standard elements for covering large areas, and by suspending their corners to a higher level cable structure, an intersubordinated cable roofing with a span of even up to half kilometers is obtained. All the advantages typical for a separate saddle-shaped cable element are presented in these structures, yet a better ratio between the covered volume and the area is observed. The obtained module of the large hierarchic structure can be combined in order to form larger roofed areas.

It is preferable to use hierarchic cable roofings for long span structures, e.g., sports grounds, concert halls, parking places. These structures can be also employed as completely or partly dismountable provisional roofings. Exploitation of long-span hierarchic roofings will provide favourable conditions for rational utilization of natural resources by developing large covered farming areas, or artificial climatic zones in areas of adverse weather conditions.

Objective of the work

To develop a rational hierarchic cable structure and determine its geometric parameters, resulting from the minimum material consumption per unit of the roofed area.

To achieve the goal, it is required:

- to develop the basic principles and recommendations of modeling hierarchic cable structures;
- to select the most rational parameters of the primary element;
- to make analysis of 3 to 4 variants of hierarchic structures and to choose one as being most rational from the point of view of material consumption;
- to develop the calculation methods of cable material consumption depending on geometric parameters and nodal displacement of hierarchic cable roofing;
- to accomplish analysis of the performance of hierarchic cable structures in case of action of various intensity wind loads and occasional snow loads.

Scientific novelty of the work

A new and rational from the point of view of material consumption hierarchic cable roof structure has been developed, which provides the reduction of material consumption from 1,5 to 2 times if compared with different long-spans structures with spans until 220 m and identical useful loads. Methods for determination of allowable displacement of bearings of primary element structure has been worked out.

It has been demonstrated that primary elements of hierarchic cable structures can not be formed without the application of composite cables with increased properties of ultimate elongation and stiffness.

Calculation methods for cable material consumption has been established depending on the main geometric parameters and nodal displacements of hierarchic cable roof, which is based on the combination of the submodels and iteration method.

Correlation between the main geometric parameters of hierarchic cable structures and the weight of cables per unit of the roofed area has been established, and recommendations for modeling hierarchic structures has been provided.

Practical value of the work

Opportunity of modeling hierarchic cable structures for roofing of long spans with subsequent for less material consumption comparing to other current roof structures has been provided.

The main rational geometric characteristic values of hierarchic structure have been defined from the view of material consumption.

Recommendations for modeling hierarchic cable structures have been presented.

The following problems are advanced for defence:

- recommendations and basic principles of the formation of hierarchic cable structures are worked out;
- calculation methods for determination of the dependence of nodal displacement and cable material consumption upon geometric parameters and the applied load of hierarchic cable roof;
- correlation between the main geometric parameters of hierarchic cable structures and the weight of cables per unit of the covered area;
- rational values of the main geometric characteristic quantities for the designed structure are determined.

Content and volume of the work

Doctorate thesis is composed of the introduction, 6 chapters, conclusion and bibliography. Volume of the work 134 pages, there are 72 drawings, 10 tables and bibliography containing 143 references.

Approbation of the work and publications

Results of the approbation work have been reported and discussed at international conferences:

- SDSMS-96 "Strength, Durability and Stability of Materials and Structures", (Kaunas, Lithuania, 1996).
- SF-99 "Modern Building Materials, Structures and Techniques", (Vilnius, Lithuania, 1999).
- 7th Int. Conf. Modern Building Materials, Structures and Techniques, (Vilnius, Lithuania, 2001).
- II World Congress of Latvian Scientists, (Riga, Latvia 2001).
- MCM-2002, 12th Int. Conf. Mechanics of Composite Materials, (Riga, Latvia, 2002).
- 8th Int. Conf. "Modern Building Materials, Structures and Techniques", (Vilnius, Lithuania, 2004).

Originality of the work has been confirmed also by patent No 12191 of Republic of Latvia. K.Rocens', G.Verdinsh', D.Serdjuks, L.Pakrastinsh "Composite Roof Structures", 20.03.1999.

The principal results of the work are outlines in 11 publications.

CONTENT OF THE WORK

Motivation of the topicality of the subject, characterization of the research unit, definition of the work, its scientific novelty and practical importance are presented in the beginning of the work.

The first chapter proposes the analysis of the present condition of cable structures, their classification, description of the applied materials and calculation methods, as well as the main advantages and disadvantages of these structures.

The first in world constructional practice negative Gauss bending cable net structure was erected in accordance with V.G.Shukhov's exhibition pavilion design in Nizhni Novgorod in 1896. The great contribution of German architect Otto Frey in the development of 3-dimensional tensioned structures is worth appreciation, because his doctor's dissertation presented unprecedented many-sided work in this area, and until the eighties of the last century he was practically the only one who was engaged in the investigation and practical realization of cable structures. Exclusively with Otto Frey's direct participation the original long - span cable structures covered with fabric were represented by German pavilion in Montreal's Expo 67' and the roof of the Olympic stadium in Munich in 1972. Investigations of tensioned structures are displayed in Geiger's, L.G.Dmitrievs, N.M.Kirsanova's, N.S.Moskaleva's, V.Kulbaha's, K.Oiger's and other works.

Roofs are classified depending on their shape in the plan (structural shape), stabilization principle of the shape of structure; kind of the cable material; kind of the supporting contour, location of the supports (inside or outside of the contour).

A detailed consideration of kinds of cable and the main physical and mechanical properties are presented, laying special emphasis on application of particularly perspective new fibres such as carbon plastic (CFC) and liquid crystal polymer (LCP) materials in the modeling of cable roofings.

It has been defined that nowadays two reinforced foil roofing types are used for external application; polyester fabric coated with PVC and glass fibre fabric coated with PTFE. Precise choice of the fabric depends on the kind of application of structure because the strength properties are approximately identical. Fabrics on polyester basis are generally used for temporary structures shorter durability and owing to their adequate folding quality. On the other hand, fabrics on the basis of glass fibre are preferably used for important permanent structures with serving lifetime more than 15 years and due to higher cost and longer durability. This material is relatively brittle and modeling of such structures is problematic.

It has been observed that cable net structures are characterized by large nodal displacements at relatively small deformations (strains) of elements. In the beginning of modeling of the structure, calculations were made by adaptation of theory of membranous shells. Due to such adaptation the calculation consists of differential equation system, the solution consists of differential equation system, the solution of which is complicated in a closed form. Most frequently these equations are solved by numerical methods such as that of finite difference. It has been concluded that the shall theory does not meet the precision requirements for cable nets with large mesh sizes, therefore it is not suitable for complicated roof structures.

Due to the development of computer technology different numerical methods have been developed, e.g., methods in the basis of potential energy minimum, dynamic relaxation technique, to say nothing of the most widespread finite element method (FEM). At first the aim of this method was to analyze structures with small deformations, yet afterwards it was modified as iterative nonlinear stiffness method. Newton-Raphson's iteration method with its original principle of application of the external load by small step increase in calculations of structures is the most advanced in solution of such nonlinear problems.

Especially, it was observed that adequate efficiency and precision was provided by the combination of Newton-Raphson technique and finite element method, hence it can be applied for most of the cable structures.

It was shown that the main disadvantages of cable structures are as follows: increased nodal displacements, relatively poor anticorrosive resistance at times, the requirement of abutment structures in taking up the abutment shear. The principal advantages of the saddle shaped cable structures have been summarized like that - new options of architectonic expression, possible translucency, light weight of structures, reduced deformability with regard to different cable structures, efficiency of high - strength material application in the production of wire construction, relatively easy erection, reduction of construction time, advantages of transportation (in rolls), good seismic resistance, cheaper fire protection methods by using foaming polymers, low cost maintenance.

The second chapter defines the basic principles of the formation of hierarchic cable structure and generalizes structures of the main components. It has been verified that the most rational for roofing maximum potential spans without intermediate supports in the development of hierarchic structures is the modulus containing 4 x 4 primary elements. Conclusion has been drawn that an easier designing process, a simplified analysis, repetitive manufacture, convenient transportability and erection are the main factors confirming the advantages of hierarchic cable structures as regular structures, and eventually lead to reduction of overall costs.

Basing on the author's, K.Rocens and D.Serdjuk's previously accomplished investigations, where rational geometric characteristic values of separately located saddle-shaped cable roofing with the compliant supporting contour and sizes in plan from 10 to 50 m are obtained, it is shown that correlation between the roofed volume and the area is unacceptable at larger spans, as it causes inexpedient increase of the heated volume. This problem can be solved by using the saddle-shaped roofings with the compliant supporting contour as standard elements, and by suspending their corners to a higher level cable structure thus obtaining a hierarchic, intersubordinated long- span cable roofing, a detailed strucrutre of the main components of which is illustrated in Figure 1.

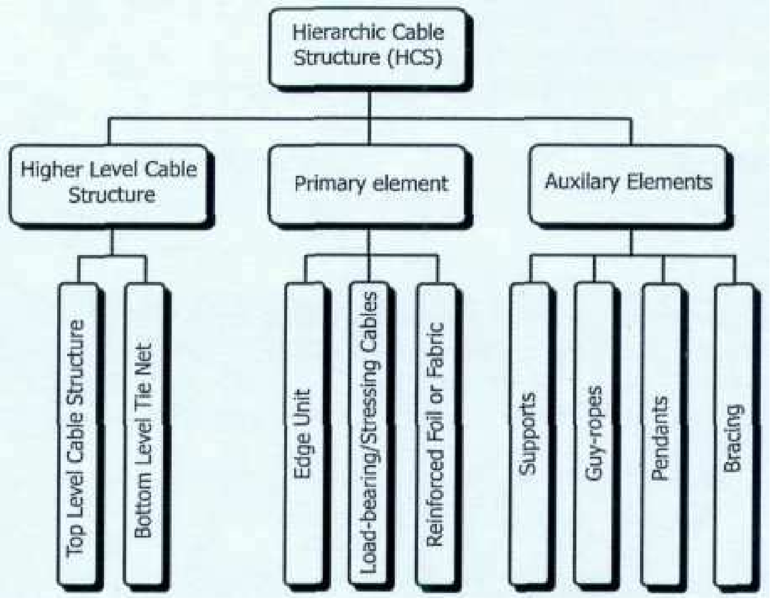


Figure 1. Classification of main components of hierarchic cable structure.

It is possible to apply the saddle-shaped roofs on various shapes of planes, yet for modeling hierarchic structures only rectangular shape variant is the most efficient, because it has the smallest number of distinctive elements, which in its turn lightens the production and erection processes. In addition, unlike rhombic saddle shaped roofings which form star-type separately situated concentric elements, there is an opportunity to expand the structure in the required direction.

Basing on the above-mentioned modeling principle of hierarchic structures, these can be formed with at least 4 primary elements (ratio of edges 2x2 elements). However, this variant is not perfectly suitable to the hierarchic principle, since not a single primary element is entirely supported by a higher level cable structure. Structure with real hierarchic principle is the one, which consists at best of 9 (3x3) primary elements, and where at least one primary element in the middle is completely suspended to a higher level structure. This structure is divided into two parts: the top higher level cable structure, where the top supporting nodes of primary elements are suspended, and the bottom higher level cable structure to which accordingly the bottom supporting nodes are suspended.

Proceeding with the expansion of a span of hierarchic structure and in order to maximize roofing of spans without intermediate supports, a hierarchic structure with 16 (4x4) primary elements and with a number of possible configurations of various higher level structures has been developed. Further increase of the number of primary elements up to 5x5 and more is irrational, since a larger number of primary elements require that they should be supported in more than two points of a higher level cable structure. Consequently, realization of the initial condition of these nodes during the erection, and restriction of displacements during exploitation gets problematic which require lest stresses in the stressing cables should reduce below zero and the element should lose its stiffness under unfavorable load combinations.

It was established that the following advantages are typical of a hierarchic cable structure as a regular element:

- relatively small complete set of components for the production of structures is needed, which enables to reduce the cost by manufacturing identical elements in large industrial line productions;
- a small amount of different cutting patterns can be made for reinforced foil or fabric;
- a small variety of elements promotes a more precise performance of the erection works;
- in case of need the structure can be easily supplemented with the same type of elements in the required direction (e.g., the structure can follow the expansion of area of archaeological works);
- a scheme of regularly repeating structure enables to reduce the dimensions of numerical model by using only several representative parts and by taking into account the impact of this part on the rest of components (subregional methods);
- repeatability provides generation of great variety of architectonic shape;
- a convenient replacement of the damaged element.

The above-mentioned advantages provide to compete with costs of hierarchic cable structures with other long-span coverings.

The third chapter presents a detailed analysis of various kinds of hierarchic structures depending on the shape in plan, the number of primary elements and supporting structures. Various advantages and disadvantages of structural solutions have been outlined there. Component parts of higher level cable structures, i.e., the main load-bearing cables, specific character of operation of the bottom tie bar net and suspenders of the primary elements depending of the span, number of nodes, cable length and possible displacements of the supporting nodes of a primary elements have been analyzed. Topology and variants are also presented.

Conclusion was made that notwithstanding the smaller number of elements, the scheme with slanting suspenders has obvious disadvantages: too long columns, which entail too large top corner vertical displacements of the bottom level standard elements, as well as large horizontal forces in these due to the angle between the suspenders and vertical axis, which may require the strengthening of standard element. Roofing scheme with vertical suspenders is assumed as most rational one.

It is verified that the plane bottom tie bar net is peculiar due to irrational material consumption and for that reason the bottom higher level structure shall be shaped by upward curvature deflection.

It was concluded that structures on a square plane with the number of primary elements 4 x 4 are recommended as a rational solution, because it will promote the development of less loaded top higher level cable structure with a minimum number of elements, a reduced cable length and the height of load-bearing columns if compared with rectangular variant with identical dimensions of the primary elements.

Not to exclude the possibility of expanding the structure in longitudinal direction of the modulus, transversal direction variant of the main bearing cables was assumed and suitable distribution scheme of columns was applied. Hierarchic modulus of a structure consisting of 4x4 primary elements, which may be intercombined for obtaining larger roofed areas was developed.

By bringing down the top higher level part of the cable structure below the level of primary elements, and at the same time by lifting their corners by means of vertical grated posts fixed to the newly developed structure, the reduction of total height of structures is achieved. In same cases they may be used as tensioning device.

The modeled variant of hierarchic structure modulus is shown in figure 2.

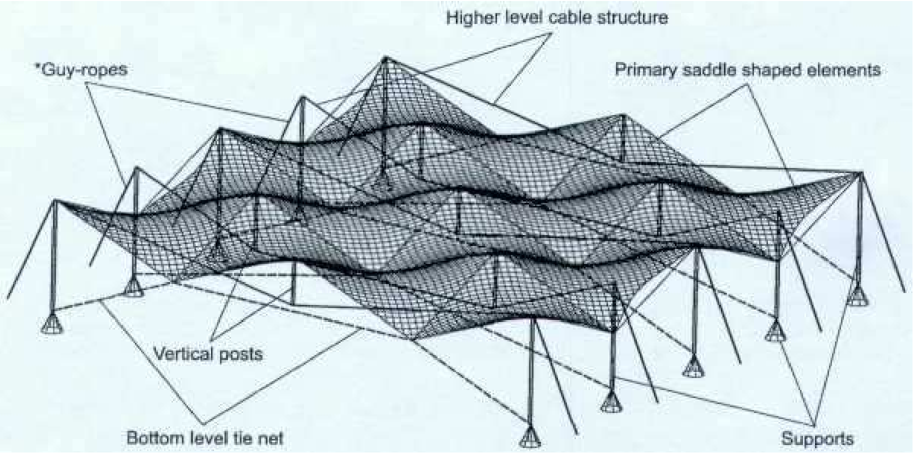


Figure 2. Simplified variant of hierarchic cable structure module
*Guy-ropes in longitudinal direction of module have not been conventionally displayed

The developed rational modulus of expandable hierarchic structure is characterized by minimum number of elements, reduced cable length and the height of load-bearing columns.

The fourth chapter presents the working out the determination methods for admissible displacements of corners of structures in the primary element, and carrying out the calculations of saddle shaped primary element structure. Basing on the results of the calculation, the advisable material properties of cables are stated and admissible ultimate displacements of saddle shaped primary element corners are assumed.

For investigation of a detailed work of a structure the following dimensions of primary elements are proposed: 35 x 35 m, 45 x 45m, 55 x 55 m.

A prestressed cable net with a negative Gauss bending type saddle shaped hyperboloid surface covered with fabric or reinforced foil has been assumed as the structure of the primary element. The primary element is formed by orthogonally crossing concave load bearing and convex stressing cables. Lest the roofing should lose stiffness, it must be provided that under most unfavourable load combinations stresses in the stressing cables should not be reduced to zero, because in the points of slack cables destructive flatter and roofing damages may occur.

On a square plane the saddle shaped structure of the primary element is assumed to have identical curvature both for load-bearing and stressing cables, because depending on the direction of vertical loads the functions of cables are interchanged. Stressing cables change to load-bearing ones and vice versa. Initial deflection values for the numerical experiment are presumed as 1/20; 1/10; 1/5; 1/2.5 parts of the span of primary element in accordance the literature recommendations. Calculation scheme of the primary element is illustrated in figure 3.

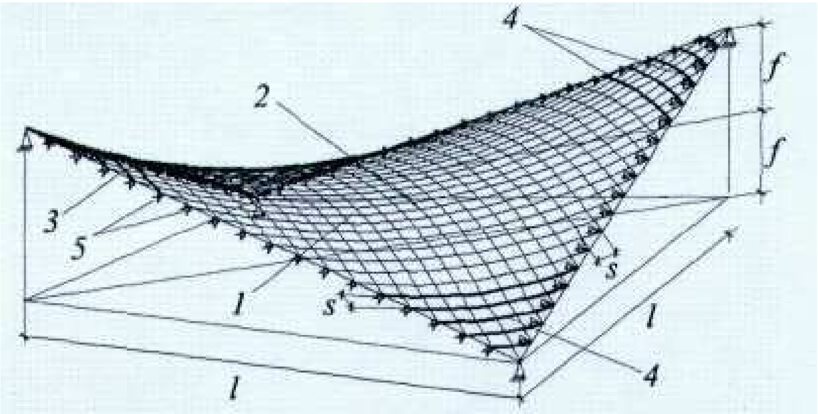


Figure 3. Calculation scheme of primary element.

1, 2 - load-bearing/stressing cables; 3 - edge cable; 4 - LCP Vectran® composite cable; 5 - symmetry boundary conditions; *l* - span; *f* - initial deflection of load-bearing/stressing cables; S - load-bearing/stressing cables spacing; fabric covering have not been conventionally displayed.

In the middle part of hierarchic cable structure the edge unit of the primary element is shaped as an up upright cable, which is symmetrically loaded with horizontal forces developed from the load-bearing or stressing cables of adjoining primary elements. In case of uniform distribution of the load, these forces are intercom pen sated, which enables to reduce the material consumption on account of the edge element. During calculations of the primary element the above-mentioned scheme promotes to apply the limiting conditions of symmetry and brings closer its action to the element with rigid supporting contour, which considerably reduces the deformability of the primary element. The edge unit of outer primary elements is modeled as a stretched on convex cable loaded with the large uncompensated horizontal load coming from the cable net. We choose the curvature of these elements equal to 1/15 part of span, basing on the assumption net the edge unit can be treated as freely suspended cable loaded with distributed load. In this case modeling of an upright rigid edge unit with length size 35 m is irrational due to large bending moments. To reduce the total deformability of the primary element and, basing on our previous investigations, the edge unit is modeled as a cable truss. The stressing value of the board elements is assumed as 1/2 from the design strength to avoid from slack of the edge unit in case of separate load combinations.

The step of the cable net is assumed 1,77 m depending on the constructive conditions lest rain bags should develop, because the fabric or some other kinds of tiling in cable net structures mainly provide the transfer of external loading to the cable net.

In accordance with the literature recommendations identical level of prestressing for all the cables of the net proposed in the initial dimensioning of the primary element cable net, which make 22,5% from the tensile strength of cables (1/2 from the design strength). It is required to provide a uniform resistance of the opposite direction vertical loads, because the functions of load-bearing and stressing cables may exchange depending on the direction of loads. To prevent the relaxation of stresses typical of steel ropes, we take care lest stresses of the dead load and those of prestressing should not exceed 45% from the cable tensile strength at tension.

By combining the primary elements of hierarchic structure, due to the effect of external loading the commonly used edge unit of two adjoining primary elements remains upright in plan, but in the vertical projection it assumes S - shape curved line which create cable sags in the corners of the element at minimum loadings. To compensate the loss of prestressing, corners of the primary element shall be developed from composite cables with increased limiting deformation properties, which make up 7% from the total length of cables. One of such materials is recently produced Liquid Crystal Polymer (LCP) Vectran® developed on the basis of polyester molecules with regularly oriented structure along the longitudinal direction of fibres. Fibres made of this material are characteristic of minimum tendency to creep.

Acting as a component of hierarchic structure, due to its reaction forces the primary element is disposed to the influence of the loaded higher level structure, which shows in the displacements of the top and bottom supporting nodes of the primary elements in the opposite direction, i.e., reduction of the initial deflection. This for its part effects the reduction of stressing of the adjacent cables as a result of the effect of external loads.

In order to assess the maximum permissible displacements of the primary element supporting nodes without cable slack (which at the same time shows how strong a higher level cable structure should be to provide the displacements of supporting nodes), a numerical experiment for three level loading of the above mentioned variants of the primary elements was accomplished. 1 - deadweight of structures and occasional snow load (0,48 kN/m^2), 2 - deadweight of structures un negative wind load in accordance with O.Frey's recommendations when the load values proportional to the distribution of actual aerodynamic coefficients, are replaced by uniformly distributed load (0,76 kN/m^2), 3 - deadweight of structures and negative wind load with twice wind speed in compliance with literature recommendations (1,60 kN/m^2), which exceed by intensity the snow load values of a valid Latvian building codes. It should be observed that the real distribution of aerodynamic coefficients for the structure in question is not established, because model investigations in wind tunnel or computer aided simulation of the exposure of wind flow by using the mathematical appliance of fluid mechanics are needed.

The computing is accomplished by means of the finite element method software"ANSYS 7.0 University" version applying for cable modeling the universal spatial bar finite element LINK10 with three degrees of freedom in each node with specific bilinear stiffness matrix, which defines that the element works in tension only. To prevent boundless nodal displacement of structures in case of the cable slack, the element might have small stiffness $AE\text{-}10^{-6}/ L$ (A - cross section area of the element, E - modulus of elasticity and L - length of the element) across the working direction. Consideration of deadweight and temperature gradient as well as introduction of initial strain $\varepsilon^{in} = (L\text{-}L_o)/L$ (where L_o - length of the element in unstressed state) shall be provided. Length and cross-section area of the element shall not be equivalent to zero.

Status of the element is determined during the 1-st loading stage resulting from the initial strain ε^{in} (prestressing) mark. If this quantity is below zero, the element stiffness is assumed equal to zero. If the element changes its status during iteration steps, the element stiffness is introduced into the next step. To increase numerical stability of the solution of suspended cable structures, stabilization effect of prestressing is considered by extra stiffness matrix generation for the element called "stress stiffness matrix":

$$[\, S_l \,] = \frac{F}{L} \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 & -C_2 & 0 \\ 0 & 0 & C_2 & 0 & 0 & -C_2 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -C_2 & 0 & 0 & C_2 & 0 \\ 0 & 0 & -C_2 & 0 & 0 & C_2 \end{bmatrix}$$

where F - longitudinal force in the element; C_2 = 1,0/0,0 (tension/compression) in case the element has no stiffness across the working direction; $C_2 = 1{,}0/(AE/F\text{-}10^6)$ (tension/compression) in case the element has small stiffness across the working direction.

In order to calculate general stiffness, this matrix is added to the regular stiffness matrix. Since stress stiffness matrix is calculated basing on the stress state of 1-st iteration, then two iterations as minimum are needed for the solution. To improve the convergence of equation system, the program affords the opportunity to apply linear search method and automatic change of loading steps as well as the change of convergence criteria.

The experiment was made by the searching method assuming the point of reference as the state when deadweight or prestressing loads work on the structure. Since uniform values of intensity of the wind both with positive and negative values can affect the primary element, which is identical with positive values of the snow load in Latvian conditions, structural performance is symmetric to the horizontal plane, the calculations are made in two stages. The first stage defines the ultimate displacements of the top supporting nodes of the primary element downwards (in the direction of the applied load), the second one - the ultimate displacements of the bottom supporting nodes upwards opposite the direction of load application.

Experimental results show that limiting values of the supporting node displacements of the primary element are mainly dependent on the initial deflection of this element. Calculation scheme of the primary element for the first stage and regularity between the limiting values of the supporting node displacements of these elements and the initial curvature of the primary element are shown in figure 4.

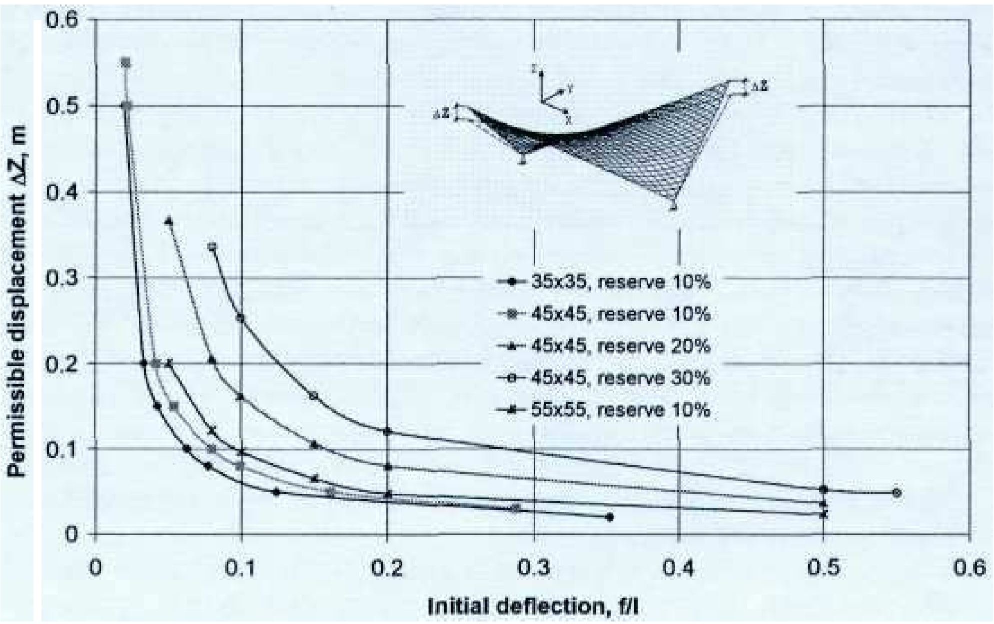


Figure 4. Permissible displacements of supports of primary element depending on initial deflection of primary element.

In order to prevent the formation of cable slack, the prestressing reserve with the limits of 10 to 40% from the total initial stressing shall be provided in the prestressing cables (increase of the cable cross-section by 1,25 to 5,0 times relatively primary element condition without nodal displacements); larger or smaller reserve is not rational because it causes a rapid increase of material consumption for the primary element in case of larger reserve and that for higher level cable structure in case of smaller reserve.

Analysis of interaction of the primary element higher level cable structure has proved that rational initial curvature area of the primary element lies from 0,05 to 0,2 f/l, which is beyond rational curvature value of 0,3 f/l of the primary element without nodal displacements.

The fifth chapter. Methodology of a detailed cable structure displacements and material consumption per covered unit area which is based on the combination of substructuring and iteration method has been developed of in chapter five.

In general tensioned structures and particularly cable net structures are characterized by nonlinear static work with variable stiffness, i.e., the displacements are not proportional to the load increase.

Nonlinear static work of cable structures is subjected to several reasons: changes of the element status (nonlinear behaviour of the structure depends on certain conditions, for example, the cable may be stressed or slack), geometric and material nonlinearity.

There are two types of geometric nonlinearity typical of the discussed structures: a) large displacements - structural performance with large nodal displacements with relatively small element strains; b) stress stiffening - increase of structural stiffness [K] with the increase of external load (geometric adoption of the applied load).

To reduce the complexity, the calculation algorithm of hierarchic cable structures includes only geometrically nonlinear structural performance, which considers the most impressive factors of the behaviour. Lest the other factors of nonlinearity should considerably effect the results of calculation, the following arrangements shall be simultaneously made. Lest the roof should lose stiffness, at each loading stage it shall be provided that the cables should not change their status (cable slack do not develop) under disadvantageous load combinations, i.e., stresses in the stressing cables should not reach zero option because damages may develop in the roofing, or destructive flattering occur. To reduce the stress relaxation effect of steel cables, it is supposed that stresses from the deadload and stressing shall not exceed 45 % from the cable tensile strength at tension. If cables from composite materials are applied, they are chosen with minimum tendency towards creep.

To reduce the total amount of the calculation, and to avoid from the convergence problems, the so-called substructuring (subregion) method for modeling of recurring system is used, which divides the structure into levels. In the first stage the required cross-sections of the primary elements cables and reaction forces of the supporting nodes are calculated, thereby collecting information (boundary conditions) for the next stage calculations of higher level cable structure. As a result of these calculations data for the next iteration are provided for calculation of the primary saddle-shaped element with new boundary conditions. Thus using of iterative approximation method the effect of interdependencies of separate structural elements and a higher level cable structure can be defined.

In the first stage of calculations concerning the initial dimensioning of the primary element cables, prestressing is assumed identical for all cables in the net, which makes up 40 to 10% from the design strength of the material also taking into account the reserve accordingly of 10 to 40% as to the supporting nodes displacement. At first the calculation was made to find cable cross-sections of the primary element under full load by method of stepwise approximation for each type of primary element and for each load level providing that no stresses exceeding the design strength of the respective material should develop in any group of cables. In the next step calculation was made with the obtained cross-sections of cables and for the load of dead weight and prestressing. To develop the reference deformed state of structure close to real structure after assembling and before exposure of live load, adjustment of nodal coordinates was made in compliance with this deformed condition of a structure after the application of deadweight and prestressing.

In the next stage a full load is applied to the primary element with corrected geometry, thus obtaining the reaction forces of the supporting nodes, i.e., boundary conditions for calculations of higher level cable structures. Further stepwise approximation method was used for higher level structures to obtain higher level cable cross - sections on condition, that at points of the load application (primary element supporting nodes) the displacements of higher level structure shall not exceed the ultimate displacement values, which were defined in the previous chapter.

The presented method has such advantages:

- it enables to calculate large and complicated structures by using easily accessible computing resources, because the component system matrixes of separate hierarchic structures are small as an direct result of subregions;
- computing time is reduced as the most part of the primary elements of structure are identical, so their calculations shall be made only once;
- computing convergence is improved;
- the time required for possible modification of structure and further repetition of the analysis is reduced, because separate parts of a structure may be left unchanged;
- it provides the access of a system to complicated calculations: structural parts may be analyzed independently, which effects positively the future design of a structure as it better harmonizes with the real design technology;
- libraries from the distributed subregional elements may be established and used in different design groups, which are engaged in similar calculations of structures;
- a complete structural model may be developed by using the multistage subregional method with the possibility to obtain the displacements and stresses in any component part of the structure, be it ever so small. For example, the design of coupling nodes, development of rain bags, or modeling by dynamic behaviour of separate parts.

The sixth chapter presents the analysis of performance of hierarchic cable structures in cases of various intensity wind loads and accidental snow loads. Regularity between the main geometric parameters of hierarchic cable structures and cable weight per unit of the roofed area is obtained. Recommendations for modeling of rational hierarchic structures are worked out.

Long span roof structures and their component parts shall be designed so that to cope safely with all the acting loads during the erection and exploitation of the structure. There are no engineering standards in the world for the present to meet specific demands and design principles of cable net structures. They are generally made basing on synthesis of the experience and on the best practical examples. Recently refined modeling methods have been developed for determination of the load value for complicated shape structures, nevertheless they involve expensive hardware, software and powerful computers.

By collecting worldwide statistics on damages and breakdown accidents of long-span structures as well as on the problems of maintenance, one can obtain information concerning the conception of failure mechanism and identify uncertainty factors effecting the safety criteria of structures. Failure of a structure is linked not only with prognosticated probability of load distribution and strength, but also include various factors, i.e., human factor, negligence, poor qualification or non-observance of some loads. Uncertainty of designing is also connected with the adequacy of structural model, which represents the correlation between the real and prognosticated behavior of the structure.

Potential factors which can influence the advancement of a structure to accidents are as follows: new or nontraditional materials, new building methods, kinds of structures, inadequate experience in organization of designing and construction teams, research and evolution background, financial conditions, industrial and political climate. That is why it is very important to make investigations which might improve proficiency concerning the problem of the performance of load-bearing structures.

The above-mentioned factors apply to long-span cable structures, and if we take into account statistical results of their failure, conclusion could be made that mostly failures are subjected to the estimation of inadequate loading. Therefore, a detailed analysis of the impact of loading in significance succession is proposed in the work. It has been observed that in accordance with the investigations carried out in the world, local dynamic instability phenomena of the roof, such, as flattering and billowing generally has no effect on the overall structure. In Latvian conditions only low frequency wind action is significant, which is taken into account by increased load safety factor or increased velocity of the wind according to Eurocode.

To determine Rational values of the main geometric characteristics of hierarchic cable structures, this structure was analyzed by means of numerical experiment by using FEM software "ANSYS University" for each experimental point value determination, and software "STATISTICA" for the combined Latin Hypercube and D-optimal experimental plan calculation and for analysis of the results, and determination of polynomial coefficient.

The following values of variable parameters for numerical experiment have been assumed: dimensions of the primary element: 35 x 35 m, 45 x 45 m , 55 x 55 m; deflection values: 1/10, 1/5, 1/2,5 parts from the span; prestressing reserve: 10%, 20%, 30%, 40% from the initial stressing; deflections values for higher level cable structure: 1/10, 1/5, 1/2,5 parts from the span. For three level loads: I - dead weight of structures and accidental snow load (0,48 kN/m^2), II - deadweight of structures and negative wind suction values are replaced by uniformly distributed load (0,76 kN/m^2), III - deadweight of structures and negative wind suction with twice intensified wind velocity (1,60 kN/m^2).

Correlation between the main characteristic values of roof and material consumption required for roofing per unit of the area has been defined as 2-nd order polynomial model:

$$\begin{aligned} C = b_o + b_1 l + b_2 p + b_3 \tilde{f} + b_4 r + b_5 \tilde{F} + b_{12} l p + b_{13} l \tilde{f} + \\ + b_{14} l r + b_{15} l \tilde{F} + b_{23} p \tilde{f} + b_{24} p r + b_{25} p \tilde{F} + b_{34} \tilde{f} r + b_{35} \tilde{f} \tilde{F} + \\ + b_{45} r \tilde{F} + b_{11} l^2 + b_{22} p^2 + b_{33} \tilde{f}^2 + b_{44} r^2 + b_{55} \tilde{F}^2 \end{aligned}$$

kur:

C - material consumption required for roofing per unit of the area, kg/m^2;

l - span of the primary element, m;

p - design load, kN/m ;

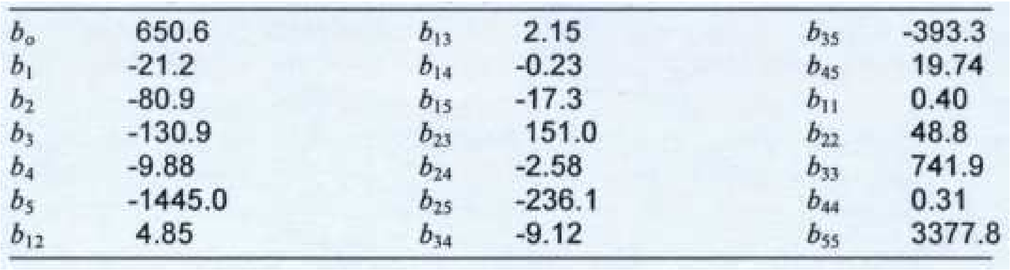
$\tilde{f}$ - initial deflection ratio for the primary element, *f/l;*

r - reserve of prestressing, %;

$\tilde{F}$ - initial deflection ratio for a higher level cable structure, *F/L.*

Polynomial coefficients are found by least squares method:

1.Tabula. Regression coefficients of polynomial model



b_o	650.6	b_{13}	2.15	b_{35}	-393.3
b_1	-21.2	b_{14}	-0.23	b_{45}	19.74
b_2	-80.9	b_{15}	-17.3	b_{11}	0.40
b_3	-130.9	b_{23}	151.0	b_{22}	48.8
b_4	-9.88	b_{24}	-2.58	b_{33}	741.9
b_5	-1445.0	b_{25}	-236.1	b_{44}	0.31
b_{12}	4.85	b_{34}	-9.12	b_{55}	3377.8

There is special feature of this experiment design, which is not characteristic of the physical experiment. The results obtained in the numerical experiment are purely deterministic without a statistical error. Replication of the results is 100%. It means that there is no statistical dispersion of the model parameters. Evidently, is not necessary to use an experiment design to replicate the observations. And for this case the adequacy of the mathematical model can be checked by value of standard deviation, which for the determined second order polynomial model is 4,78%, thus confirming that this model approximate experiment with sufficient accuracy for design purposes.

Analysis shows that the most important effect is achieved by two following parameters: the initial deflection ratio of higher level cable structure and the prestressing reserve of the primary element, the influence of which on material consumption for one case is graphically shown in figure 5. The rational values for this particular span case 180 m (span of the primary element 45x45m) and external load 0,48 kN/m^2 are: initial deflection ratio 0,288, prestressing reserve 30,2%.

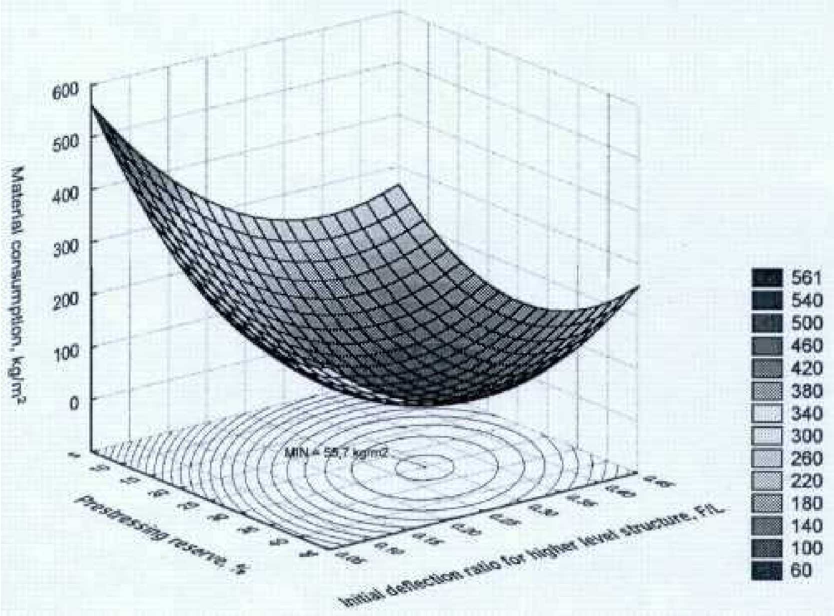


Figure 5. Material consumption of hierarchic cable structure depending on initial deflections ratio of higher level structure and the prestressing reserve of primary element (span L=180m (45x4), load 0,48 kN/m^2).

Summing up the analysis of structural performance, the following recommendations for modeling rational hierarchic structures have been proposed:

- from the constructive point of view most rational module of hierarchic cable structure should have dimensions 4x4 primary elements, the largest one is characterized by irrational material consumption for the higher level cable structure;
- to reduce the total height of structures, a part of the top higher level cables should be preferably lowered below the primary element surface with simultaneous lifting up of the corners of primary elements by means of vertical latticed posts fixed to these cables;
- the bottom higher level structure shall be shaped with upward curvature, because the plane bottom tie net is typical of irrational material consumption;
- the roofing scheme with vertical pendants shall be designed since the application of inclined ones may require the strengthening of the standard element;
- not to exclude the possibility of extension of structural modulus in longitudinal direction, transversal direction variant of the higher level cable structure is recommended;
- to prevent the development of cable slack in the primary element, a permanent reserve within the limits of 10 to 40 percent from the total initial stressing shall be provided;
- structural bracing between corners of the primary element shall be designed in order to distribute the effect caused by concentrated and horizontal wind loads.

In the Figure 6 is generalized information about material consumption of erected long-span structures depending on the span equivalent to steel:

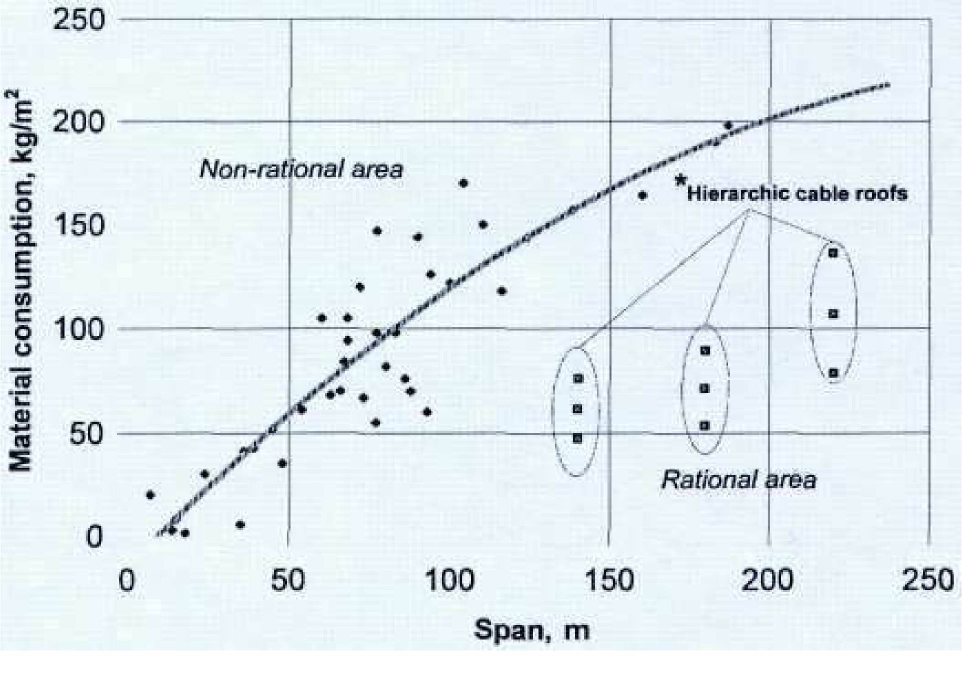


Figure 6. Material consumption depending on the span of structures

"Hierarchic cable roof material consumption is shown for three level loading

Comparing these results with characteristic values of already erected long-span various structures, one can make sure that material consumption of hierarchic cable structures lies within the rational area.

SUMMARY

Analysis of the performance of hierarchic cable structure has been made in cases of action of different intensity wind and snow loads, and correlation between the main geometric parameters of hierarchic cable structure, the design load and weight of cables per unit of the roofed area has been obtained. Recommendations for modeling rational hierarchic structures have been worked out as well.

As a result of the doctorate thesis:

- From the point of view of material consumption a new and rational hierarchic cable roofing structure enabling to reduce the material consumption by 1,5 - 2 times comparing with other large - span structures has been worked out.
- A saddle - shaped primary element structure has been developed and dimensioned, and selection of materials for components is accomplished. A determination method of permissible displacements of corners of the primary element structure has been developed.
- It has been proved that the primary elements of hierarchic cable structures cannot be modeled without the application of composite cables with increased limit of deformation properties up to 4%.
- It has been proved that due to the iteration of the primary element and higher level cable structure the rational initial deflection area of the primary element lies from 0,05 to 0,2 f/l, which is beyond rational curvature value of 0,3 f/l for a separate primary element, which is not a component part of hierarchic structure.
- Computing methods of the cable material consumption per unit of the roofed area depending on the main geometric parameters and nodal displacements of hierarchic cable roof, which is based on the combination of submodels and iteration has been developed. Rational values of the main geometric characteristics have been defined for the above mentioned structure.
- Correlation between the main geometric parameters of hierarchic cable structure, i.e., span of the primary element, prestressing reserve, deflection values of the primary element and higher level cable structure, load volume and weight of cables per unit of the roofed area has been determined, and recommendations for modeling hierachic structures are presented.
- It has been concluded that by increasing the material consumption for the primary element (prestressing reserve on account of the allowable displacements of supporting nodes), the overall material consumption of hierarchic structure can be cosiderably reduced on account of the materials used for higher level structures.
- It is shown that by means of the accessible finite element method software the forces, displacements and material consumption for complicated intersubordinated hierarchic cable roofs can be computed, and the effect of separate structural element displacements on other structural elements can be defined.
- It is demonstrated that ratio between the deadweight and live load of the presented structure is nearly twice more effective then that of analogous buildings at the identical span.

LIST OF PUBLICATIONS

1. Rocēns K., Pakrastiņš L., Brauns J. Warping of Composite Materials. *Proc. SDSMS-96, Strength, Durability and Stability of Materials and Structures,* Kaunas, Lithuania, 1996, September 18-20. PP.248 - 252.

2. Rocens K., Verdinsh G., Serdjuks D., un Pakrastinsh L. Composite Roof Structure. - *Patent No 12191 of the Republic of Latvia,* 20.03.1999.

3. Serdjuks D., Rocēns K., Pakrastiņš L. Rational Geometrical Characters of Saddle Shape Cable Roof Supported By Tensioned Cables. *Proc. SF-99, Modern Building Materials, Structures and Techniques,* Vilnius, Lithuania, 1999, May 19-21. Vol II, PP.122 -127.

4. Serdjuks D., Rocens K., Pakrastinsh L. Utilization of Composite Materials in Saddle-Shaped Cable Roof. *Mechanics of Composite Materials.* - New York, 2000, - Vol.36, No.5. - PP.385 - 388.

5. Serdjuks D., Rocens K., Pakrastinsh L. Composite Structure of Saddle Shape Cable Roof. *Scientific proceedings of Riga Technical University.* - Riga, 2000, -Vol.1 Architecture and construction science. - PP.101 -106.

6. Pakrastiņš L., Serdjuks D., Rocēns K. Some Structural Possibilities to Decrease the Compliance of Saddle Shape Cable Structure, *Proc. of the 7th Int.Conf. Modern Building Materials, Structures and Techniques, Vilnius, Lithuania,* 2001, May 16-18. PP. 24 - 25.

7. Pakrastinsh L., Rocens K. Hierarchic Cable Structures. *Scientific proceedings of Riga Technical University,* Vol.2 Architecture and construction science. - Riga, 2001. - PP.130 -135 (in Latvian).

8. Brauns J., Rocens K., Pakrastins L. Long-term creep of chipboards. *Scientific proceedings of Riga Technical University,* Vol.3 Architecture and construction science. - Riga, 2002. - PP.113 -122 (in Latvian).

9. Serdyuks D., Rocens K., Pakrastin'sh L. Prestress Losses in the Stabilizing Cables of a Composite Saddle-Shaped Cable Roof. *Mechanics of Composite Materials.* Vol.39, No.4, New York, 2003, pp.341 - 346.

10. Pakrastinsh L., Rocens K. Evaluation of Cable Material Consumption of Ties Depending on the Nodal Displacements of Hierarchic Roof. *Scientific proceedings of Riga Technical University,* Vol.4 Architecture and construction science. - Riga, 2003. - PP. 182-187.

11. Pakrastiņš L., Rocēns K. Calculation Principles of Cable Material Consumption Depending on the Nodal Displacements and Geometrical Parameters of Hierarchic Roof, *Proc. of the 8th Int. Conf. Modern Building Materials, Structures and Techniques,* Vilnius, Lithuania, 2004, May 19-21. - PP. 277 - 278.