RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
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PERMANENT AND LIVE LOAD IMPACT ON CABLE-STAYED BRIDGE'S LOAD-BEARING ELEMENTS

Summary of the Doctoral Thesis
RTU P-06 Doctorate Board

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Riga City 2013

UDK 624.5(043.2)
St 693 p

V. Straupe. Permanent and Live Load Impact on Cable-Stayed Bridge's Load-bearing Elements.
Summary of the Doctoral Thesis
- Riga City, RTU, 2013- pages 27.

Printed in accordance to the Decision of the Doctorate Board "RTU-P06" Dated 28 June 2013, Minutes No. 6-2013

This work has been supported by the European Social Fund within the project "Support for the implementation of doctoral studies at Riga Technical University – 2."

EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

ISBN 978-9934-10-462-6

DOCTORAL THESIS NOMINATED BY THE RIGA TECHNICAL UNIVERSITY FOR OBTAINING DOCTOR'S DEGREE IN ENGINEERING

Doctoral Thesis for the Degree of Doctor of Engineering will be presented to the public on 22 November 2013 at the Riga Technical University, Faculty of Civil Engineering, at 16/20 Āzenes Street, in the Chamber.

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CONFIRMATION

I hereby confirm that I have developed this Doctoral Thesis, which has been submitted for consideration to the Riga Technical University, for obtaining the Degree of Doctor of Engineering Science. The Doctoral Thesis has not been handed in to any other university for the purpose of obtaining an academic degree.

Verners Straupe ……………….........

Date: ………………………

The Doctoral Thesis is written in Latvian language, contains the Introduction, 5 Chapters, Conclusion, Bibliography, 3 Attachments, and 77 Illustrations. The content of the Thesis is presented on 138 pages in total. The bibliography lists 104 references.

GENERAL WORK DESCRIPTION

Relevance of the Subject

In recent decades, the world witnessed rapid development of the cable-stayed bridge system. The number of cable-stayed bridges is increasing, diversifying their design solutions, while various cable system computation methods develop over time. As a result of the introduction of new materials, today it is possible to cover increasingly longer spans. Simultaneously, reduction of material consumption results in the higher cost-effectiveness of cable-stayed bridges. Complex cable system designing requires the development of computation methods (generalisation) for the purpose of finding economically rational solutions, while not compromising on the structural safety. Tensile force adjustment in cables is a means of reduction of the strain in the other load-bearing elements, namely, the stiffness girder and pylons, thereby facilitating constructive solutions and reducing costs.

The author of this Doctoral Thesis is working on the analytically derived correlations, which describes the stiffness girders, pylons and cables mechanical and geometrical properties impact on the displacements and strains in the system. By applying structural analysis methods, continuous functions are found describing the considered problem which are differentiable and thus suitable for search of extreme points. A good understanding of the interconnections of these indicators enables to make a reasonably accurate initial assumption of element properties for further examination with the Finite Element Method (FEM).

Objective of the Thesis:

To develop a new method for theoretical analysis of cable-stayed bridge's load-bearing elements that allows carrying out assessment of the geometrical and mechanical parameters impact on the structural behaviour and the criteria specified for the load bearing capacity. In comparison to the traditional methods of analysis, interaction laws obtained shall be continuous and differentiable functions over the entire region of cable stayed bridge realistic parameters; also, they shall reflect the rate of change of the test criteria dependence on the geometrical and mechanical input data variations.

Aims of the Thesis

1) To develop a new method by what displacements – strain interaction laws in symmetrical cable system can be analytically studied as continuous functions.
2) To apply the developed method to study the cable-stayed bridge system behaviour under uniformly distributed and concentrated moving loads by analysing the differential equations of deformed shape of axle; to identify the efficiency of innovative "active" cable system in order to reduce strains caused by moving load.
3) To determine efficient division of the stiffness girder that offers the possibility of reducing the stresses within the span and cables.
4) To demonstrate the efficiency of the developed method with the use of practical examples.

Defendable thesis:

1) New method to analyse interaction laws in the cable-stayed bridge's load-bearing elements and assess impact of geometric and mechanical parameters using continuous and differentiable functions.

2) Adoption of the developed method for the determination of innovative "active" cable system operation principles.

Scientific novelty

Traditionally, determination of rational cross-section and arrangement of the cable-stayed bridge system elements is an iterative process, in which a solution that satisfies both the limit conditions set for the structural behaviour, as well as economic considerations is gradually approached, with a high number of finite element methods computations.

In the Doctoral Thesis for the first time the cable-stayed bridge's load-bearing elements are being described by analytical continuous and differentiable functions, derived by precise structural analysis methods analysing the deformed shape of the system, enabling to find the significance of interaction between the elements of the system, as well as to determine potential extreme points.

Based on the analytical approach, a number of recommendations has been made for rational system geometry improvements, as well as a method is developed for an easy and reasonable assumption of cable bridge elements mechanical parameters for their further verification with the finite element method computations.

In addition to the developed analysis methodology, usefulness of the "active" cable system is being evaluated in the Thesis. With an active cable system here and elsewhere shall be understood the mechanism, which depending on the position of the moving load on the carriageway, applies tension in certain cables, reducing displacements as well as strains of the stiffness girder. Study of such system would allow for the possibility of using new materials in cable manufacturing, which feature extremely high strength, while due to low Young's modulus large displacements noncompliant with the usability criteria of structure appear within cables.

Practical significance of the research

Bridge structures, that are characterised by small material capacity and are cost-effective alike, need to be developed in the Latvian bridge construction industry. Cable-stayed bridge economic efficiency is dependent on the rational use of components load-bearing capacity; therefore it is necessary to carry out scientifically well-founded theoretical studies of the interaction between elements in cable stayed bridges.

Several long-span bridges are planned at preliminary design stages in Latvia, where the spanning of the central span will require use of cable or suspension systems:

- Bridge over the River Daugava in Riga (Northern crossing with a central span of ~ 400 m);
- Bridge over the River Daugava in the town of Jēkabpils (the bridge passage length is 420 m, and central span of 260 m; in 2013 JSC "Ceļuprojekts" has developed a conceptual cable-stay bridge design, which takes into account the findings obtained in the Thesis);
- Bridge over the River Daugava at Salaspils (the bridge passage length of ~ 1200 m, the central span of ~ 440 m).

The results obtained allow finding rational, safe and at the same time innovative cable-stayed bridge's geometrical and mechanical parameters. The developed analytical method can be used not only for the bridges, but also for designing roofs of other structures (e.g. covered stadiums, covered parking, etc.)

Restrictions of the Research

The following input data shall be included into the mathematical derivation:

1) cable system's geometric properties:
   a) span length and division in panels (the distance between the cable anchorpoints);

   b) the number of cables;
   c) cables inclination angle;
   d) the height of the pylons;
2) the cable system's component mechanical properties:
   a) the cables tensile stiffness ($E_v F$);
   b) the bending stiffness of stiffness girder ($E_s I_s$);
3) loadings:
   a) permanent load (selfweight, which can be generalised as a function of geometric dimensions of the load-bearing elements);
   b) live load – the moving traffic loads in various unfavourable placement combinations conforming to the current codes.

With the proposed analysis method impact of the defined input data on the main limit conditions shall be found and mapped graphically:

1) the allowed displacements of stiffness girder;
2) the allowable stresses in cable stays;
3) the allowable stresses in the stiffness girder;
4) the search of considerations to find minimal possible bending moments.

Generalised mathematical derivation is easily adaptable to following most popular cable-stayed bridge systems:

1) with two pylons and one central span (symmetrical model);
2) with two pylons, one central and two side spans (symmetrical three span model);
3) a single pylon and one span (asymmetrical model);
4) with a single pylon, one central and one side span (asymmetrical two-span model).

Broadest objective of the research conducted is to get a mathematically grounded idea of the relationship between the defined input data and limiting parameters.

This analysis should serve as a tool for purposeful assumption of the cable system elements geometric and physical properties, which shall be further verified by detailed calculations for each specific case. Therefore, this Thesis does not address following factors:

- the study examines only two-dimensional model of structures, not taking into account live load shear distribution and other three-dimensional effects;
- the study examines only selfweight and live load effects, not taking into account other variable effects – temperature gradient, support settlement, wind, snow and ice loads, extreme actions (impact of motor vehicles, etc.);
- the study examines only the static performance analysis, not taking into account vibration, and other dynamic effects.

Research methodology and theoretical basis

The Doctoral Thesis proposes a solution where the classical (exact) methods of the structural analysis are used for complex statically undetermined, geometrically and physically nonlinear system analysis.

The cable system performance research has been carried out in two ways. First of all, an inductive analysis was conducted – knowing the general requirements that are set out for completed structures, there are defined criteria to be met (e.g., the minimum possible bending moments or tensile stresses in the stiffness girders) and search for system input values that provide it. In this case, the mathematical functions are found, in which a search criterion is variable, but the function values are certain geometric or mechanical parameters of the system.

Following this, the deductive inference was performed, intended for any cable system analysis and searching for the functions that show geometrical and mechanical parameters impact on the system's final verifications (bending moments, stresses and displacements).

In both cases, the stiffness girder performance has been studied using precise structural analysis methods. In the first case differential equation of deformed shape of axle of multispan continuous beam is solved and in the second case the bridge span structure is studied as a continuous beam on elastic supports using the displacement method. Cable stays were examined as rods subjected only to tension, taking into account their end point displacements non-linear dependence on the tensile strength in cable stays, which is related to whole cable stays rotation in a vertical plane. In particular cases, the resulting multivariate functions also allow construction of particular parameter influence line.

First, a theoretical inference was made for the two described approaches, then its possibilities shown in the example, and finally the accuracy and precision of the results were verified, by comparing typical points of certain features found to results from the finite element method (FEM) calculation. Performing these verifications particular attention was paid to the area of the resulting optimal solution (function maxima and minima). The three aforesaid research stages are described in the Doctoral Thesis Sections 2, 3 and 4.

The structure of described work is presented in the following diagram.

Structure of the Doctoral Thesis (by Sections)

The line of research / Research stage	Ascending (inductive) reasoning			Descending (deductive) reasoning. Generalised derivation
	Permanent load	Live loads		
		Impact of moving load	Operation of the "active" system	
Development of theoretical basis	2.2	2.3	2.4	2.5
Study of the use, with examples	3.2; 3.5	3.3	3.4	3.6
Verification of the results	4.1	Appendix	Appendix	4.2

Theoretical derivations are mostly performed by the mentioned structural analysis methods. MathCAD engineering software was used for the resulting functions graphical display for search of the extreme points, and for solving proposed algorithms. Verification of certain points was performed by a nonlinear FEM model in LIRA software.

The Doctoral Thesis features a reasonable theoretical basis and the resulting mathematical algorithms for different cable bridge systems to develop computer–based program, which could be used as a means of initial assumption of geometrical and mechanical properties.

Structure and contents of the Doctoral Thesis

In theoretical part of the Doctoral Thesis research, which is mainly addressed in the Chapter 2, only the final derived functions are given. Full output, as well as MathCAD programmed algorithms are enclosed in the Appendixes. Only summary of sections describing the desired bending moment diagram acquisition from permanent loads is included, as this study has been carried out already in Master's Thesis "Analysis of calculation method for cable-stayed bridge cable adjustment" (2004) carried by the author of this Doctoral Thesis.

The Doctoral Thesis consists of the general characterisation of the study, five chapters, conclusion and bibliography.

Approbation and publications of the Doctoral Thesis

Results of the Doctoral Thesis have been published in the following scientific journals and discussed at the following international conferences.

Articles published in scientific journals that are indexed in SCOPUS International Database:

- Straupe V., Paeglitis A. Analysis of Interaction between the Elements in Cable Stayed Bridge // The Baltic Journal of Road and Bridge Engineering. – Vol.7, No.2. (2012.) pp 84 – 91.
  ISSN: 1822-427X
- Straupe V., Paeglitis A. Analysis of Geometrical and Mechanical Properties of Cable-Stayed Bridge // Procedia Engineering. – Vol. 57 (2013, Elsevier Ltd.) pp 1086 – 1093.
  ISSN: 1877-7058

Article published in conference proceedings, which is indexed by the SCOPUS international database (with international scientific conference report):

- Straupe, V., Paeglitis, A. (2012.) Structural Reliability of Cable Stayed Bridges Based on Analysis of Deformation // IABMAS 2012 „6th International Conference on Bridge Maintenance, Safety and Management", Stresa, Lake Maggiore, Italy, 8.-12. July, 2012; *Proc.* In: Biondini, F., Frangopol, D., M. (Eds). Bridge Maintenance, Safety, Management, Resilience and Sustainability. Taylor & Francis Group, London, 3880-3887.

ISBN: 9780415621243

Article published in the RTU collection of scientific papers (journal)

- Straupe V., Paeglitis A. Symmetrical cable systems with a central span, an analytical study // Scientific Proceedings of the RTU. Series 2., Civil Engineering. - Vol. 5 , (2004)., pp.236-245.
- Straupe V., Paeglitis A. Some cable computational aspects of the cable-stayed system bridges // Scientific Proceedings of RTU. Series 2, Civil Engineering. - Vol. 4. (2003), pp.216-223.

Articles included into the conference full-text collection of articles (with a report at the international scientific conference.)

- Straupe V., Paeglitis A. Cable-Stayed Bridge Elements Lifetime Optimization Model // 18th IABSE Congress „Innovative Infrastructures - Toward Human Urbanism", Korea Republic, Seul, 19.-21. September, 2012. - pp 1-8. *ISBN:* 978-3-85748-127-7
- Straupe V., Paeglitis A. Mathematical Bases of Interaction between Elements in Cable Stayed Bridges // 35th Annual Symposium of IABSE Taller, Longer, Lighter, Meeting Growing Demand with Limited Resources: Proceedings, United Kingdom, London, 20.-23. September, 2011. - pp 1-8. *ISBN:* 9780707971223

Articles included to conferences abstracts collection (with an international scientific conference report)

- Straupe V., Paeglitis A. Optimization of Cable-Stay Bridge Elements // Riga Technical University 53rd International Scientific Conference: Dedicated to the 150th Anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU

Alumni: Digest, Latvia, Riga, 11. – 12. October, 2012. – p 406.
ISBN: 9789934103605

- Straupe V., Paeglitis A. Analysis of Cable-Stayed Bridges Load-bearing Elements // Joint World Congress of Latvian Scientists III and IV Lettonic Congress "Science, Society and National Identity": Section "Technical Science": Abstract Book, Latvia, Riga, 24th - 27th October, 2011., p. 59.
ISBN: 9789934102271

<u>Report at the international scientific conference without abstracts</u>

- Straupe V., Paeglitis A. Analytical study of cable-stayed bridge load-bearing elements // RTU 51st International Scientific Conference, Section "Civil Engineering", Riga, Latvia, 11th-15th October, 2010.

<u>Participation in the state research program</u>

- The State Research Programs No.2011. 10-4/VPP-5, Project No. 4: "Safe and Sustainable Road Transport Infrastructure Development (DIATIA)"

CONTENTS OF THE DOCTORAL THESIS

Chapter one

The historical development of the modern cable-stayed bridges dates back to the middle of the 19th century, with numerous failed attempts to construct such structures. The first successful cable-stayed bridge (in the modern sense) was built in Sweden in 1955; twisted steel cables were already in use for the cable stays. Rapid development of cable-stay bridge design solutions and calculation principles began in the coming decades. Today there are already three cable-stayed bridges around the world with a central span exceeding the length of a 1 km.

The Doctoral Thesis shortly describes the classification of cable-stayed bridge load-bearing elements and shows the most popular design schemes which differ mainly in the number of pylons and arrangement of cables. Most attention is paid to the calculation principles of cable-stayed bridges. Among them the cable adjustment (control) concept to achieve desired result plays very significant role. Most popular calculation considerations for cable stay prestressing are included into the following traditionally applied methods:

- optimisation method;
- zero displacement method;
- force equilibrium method;
- the principle of virtual work.

At the conclusion of the Chapter the need for conducting the Doctoral Thesis research is explained.

Chapter Two

The principles of developed calculation methodology and structured sequence of actions to be performed are described.

The cable-stayed bridge's central span at uniformly distributed load (e.g., self-weight) is analysed. The aim pursued by the regulation of the cables is defined: the acquisition of bending moment diagram, where maximal of the positive and negative absolute values is equal – see. Fig.1. It is feasible to solve the task by dealing with other criteria. Calculation derivation reveals that such moment diagram occurs at certain vertical displacements of the stiffness girder's elastic supports (cables). By solving the differential equation of deformed shape of axle caused by distributed load and vertical components of cable tensile forces, the functions that display the stiffness girder and cable stiffness impact to the sought displacements are found. By taking into account the assumed inclination angles of the cables (that is related to the pylon height) and the effect of rotation caused by deflection, necessary parameters are determined, that provide required displacements of characteristic nodes.

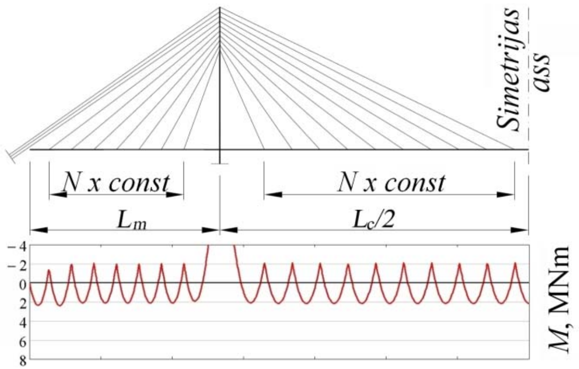

Fig.1.Preferred bending moment diagram

The same calculation considerations were repeated to find ways to reduce stresses in the stiffness girder arising from the self-weight load. This calculation takes into account the axial force in the stiffness girder from horizontal components of cable tensile forces, which also depends on the construction technique used in the assembly.

Proposals are also given for rational arrangement of cable anchorpoints at the stiffness girder, which helps to reduce maximum stresses.

In the second chapter the solution is found that demonstrates the impact of moving concentrated load (that represents traffic loads) on the bending moments in the stiffness girder. The smallest theoretically possible bending moment maximal values can be obtained by "actively" tensioning and releasing certain cables, while concentrated force is moving across the bridge. Working principles of such innovative "active" cable system are analysed. They indicate that for acquisition of the desired bending moment diagram, no cables are to be released under the tensile force values resulting from the permanent loads, so there is no reason to be afraid that certain cables could be excluded from operation. This property is also demonstrated by the "active" action movements of corresponding anchorpoints, which all are positive (directed upwards) – Fig.2 demonstrates "active" displacements of three arbitrary selected anchorpoints depending on the position of the point load.

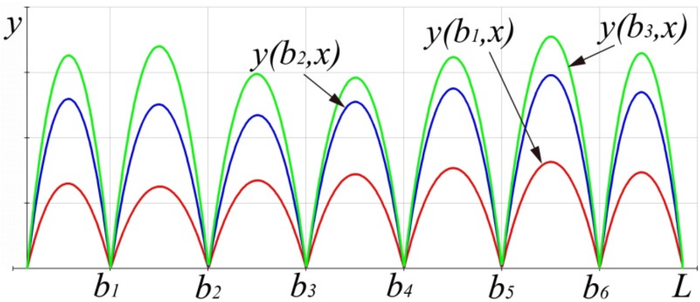

Fig.2 Anchorpoint "active" displacement dependence on the point load position *x*

So far the considerations described are tended to find input parameters of cable-stayed bridge, so that the defined result could be achieved.

Next a mathematical derivation is performed, which shows how arbitrary selected input data impacts the verifiable criteria. This derivation is gained by the displacement-based method, assuming the span as a girder supported on elastic supports in cable anchorpoints (see Fig. 3). Factors of supporting springs are determined from the corresponding cable parameters – stiffness, inclination and length. The rigid supports (at the ends of span and at the pylons) are represented by indefinitely large spring factors. Thus, the derivation of stiffness girder can be used for any cable system, in each calculation analysing the impact of number and location of pylons, as well as impact of cable geometrical and mechanical properties on the spring factors.

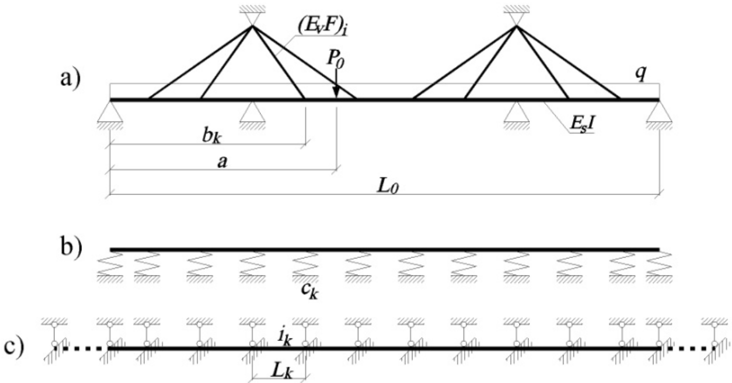

Fig.3. a – bridge layout, b – design layout, c – displacement method base layout

Spring factors dependence on the properties of cables is non-linear, as inclined cables turn in vertical plane, when one of its ends is displacing in a direction not parallel to the longitudinal axis of the cable. However, examination of the least possible inclined cable (the smallest practically used angle) at the maximum allowable deflections defined by the bridge construction codes, shows that the impact of this non-linear effect on the spring coefficients does not exceed 1.3%. This effect can be considered as negligible.

The second noteworthy nonlinear effect of inclined tensile cable is its self-weight resulted sags dependence on tensile force. This effect can be evaluated, if idealised Young's modulus that is a function of the cable tension force is used, instead of the real value. The proposed analysis methodology makes it possible to use the Young's modulus as a function with the unknown – tensile force in cable stays caused by corresponding loads.

Chapter Three

Two design examples are presented where developed derivations of the cable-stayed bridge elements interaction analysis methodology are used:

1) a system with two pylons, a central span (L = 231m) and three symmetrically arranged pairs of cables;
2) three-span system (span layout: 80m + 260m + 80m) with two symmetrically placed pylons and cables; this structure is designed for a new bridge over the River Daugava in Jēkabpils sketch design (2013).

For the firsts structure the following criterion has been defined – to obtain bending moment diagram from the uniformly distributed selfweight load with the same absolute values of the moment extreme points in each panel of the stiffness girder. Stiffness girder node displacements, which fulfil defined criterion, as well as the corresponding cable properties, are found.

Considering that the analytical method uses functions that show the impact of the input data to the set limit condition, it is possible to graphically represent this interaction which helps finding the most convenient (most economical) way to achieve the desired result. Some of typical interrelationships are shown in Figures 4, 5 and 6.

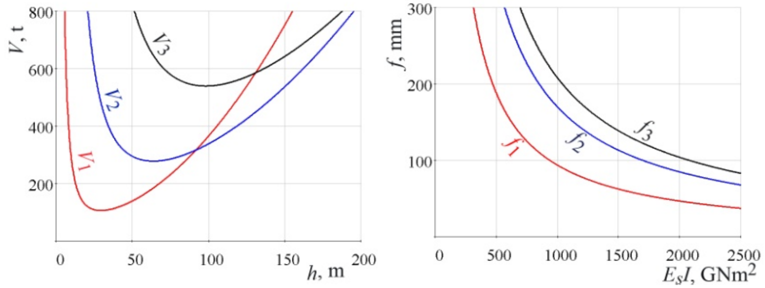

Fig.4. Cable steel consumption dependence on the height of the pylon (left) and anchorpoint displacement dependence on the stiffness of the girders E_sI (on the right).

The results allow to draw a conclusion that from the point of view of cable material economy, a parallel cable layout is rational solution. Minimal cable cross-section can be used in 54° sloped cable, whereas the lowest total mass of cables is for the layout with cables inclined 45° degrees.

Slope (rate of increment) of the graphically depicted functions allows conducting analysis of the stiffness girder and the cable cross-section increase impact on the required node displacements.

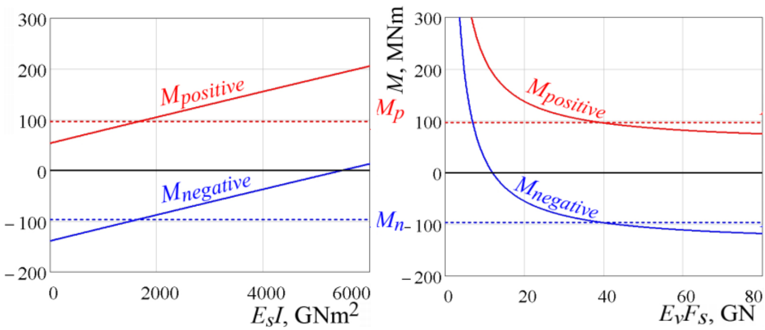

Fig.5. The bending moment maximal values dependence on the stiffness of the beam (left) and cable (right) stiffness

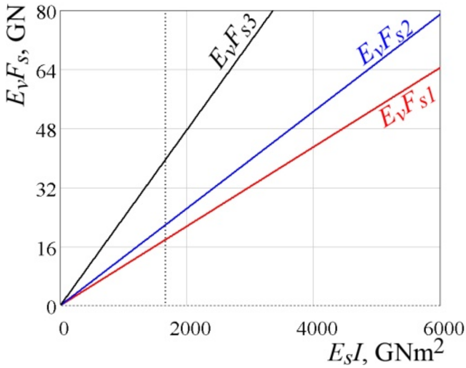

Fig.6. Stiffness required for three cables depending on the stiffness of span

Overall, it should be concluded that the system works according to the physical principle: "the strongest element works more than others" – namely, in stiffer elements higher forces occurs. This leads to the paradoxical outcome: the idealised bending moment diagram can be obtained by reducing the stiffness of all load-bearing elements (Fig. 6). However, it has significant impact on the serviceability limit state requirements defined in construction codes – allowable displacement, which remains a key factor for choosing the design parameters.

With the same bridge model the postulated judgments about the impact of moving loads as well as bending moment reduction to the theoretically smallest possible values using the “active” cable system are tested. Calculation considerations allow to define an operating principle for this kind of system – “active” operation of cables is needed for cables that are anchored at both ends of panel with a concentrated load, as well as for the two outer cables – see Fig.7.

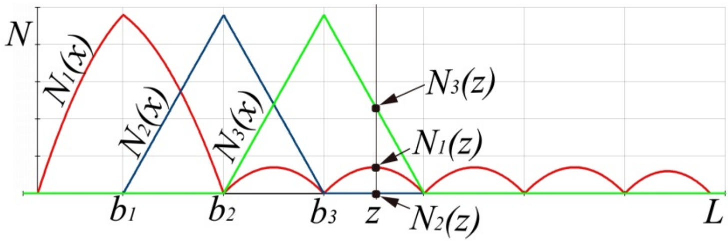

Fig.7. "active" adjustment forces of three cables dependence on the location of concentrated load

Some experiments with the developed mathematical model show that efficiency of "active" cable system can be described as:

$$\eta = \frac{S_{permanent}}{S_{total}}, \quad (1)$$

where: $S_{permanent}$ – permanent force (bending moment of the stiffness girder, tensile force in cables, etc.);

S_{total} –- total maximum force, obtained by taking into account live loading (traffic load, wind, temperature, etc.).

Increase in the value of the parameter η, decreases the "active" system efficiency and vice versa. Therefore, attention to such system should be paid to when dealing with structures that have slender stiffness girders and a relatively low selfweight.

The advantage of stress reduction is based not only on economic considerations – reducing material usage. Also reduction in the stress fluctuation range (difference between maximum and minimum stress values) serves for reducing the fatigue effect. With a separate analysis it is possible to assess the "active" systems construction reliability index β, which is defined by the construction code LVS EN 1990 "Eurocode. Basis of structural design."

With the help of second cable bridge model the solution to reduce the maximum stresses in stiffness girder is sought. They are influenced by the horizontal components of the force applied at the cable anchorpoints. Impact on a completed structure is dependent on the erection method of girder during construction. The two most popular methods of erection are compared:

- erection of girder using temporary supports followed by the connection of cables;
- erection of girder using cantilever method, starting from pylon gradually adding panels and cables step by step on each side.

For reinforced concrete bridge structure (as discussed in the example) it is essential to limit the maximum tensile stresses in the middle of the central span. This can be achieved effectively by modifying the structure in such a way that the cable anchorpoints are placed with varying steps, so that every next step in direction away from the pylon is shorter by a constant value *dx*. Impact of this parameter on the maximum tensile stress in stiffness girder for both erection techniques are shown in Fig.8.

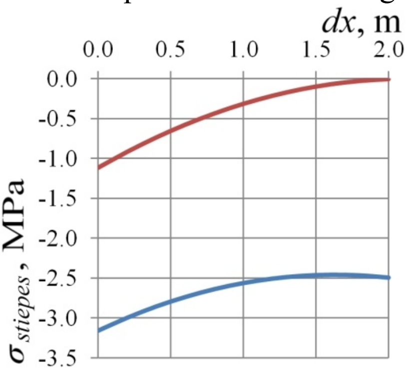

Fig.8. Maximum tensile stress dependence on the parameter *dx* (blue line – erection using temporary supports, and red line – erection using cantilever method)

It is determined that parameter *dx* has a positive effect on the tensile force distribution between cables – it is possible to find a value that gives approximately equal force in all the cables (see Fig.9). However, the optimal value of *dx* differs when derived using two previously mentioned criteria. Compromise should be made in every individual case.

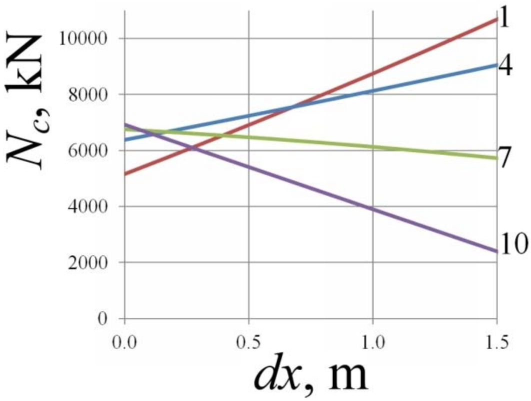

Fig.9. Cable tensile force dependence on the parameter dx (four of the 10 central span cable pairs are shown)

Second proposed cable bridge model is used to test developed deductive analysis derivation – internal force, curved axis and cable force functional dependence on arbitrary input data, which is reduced to a calculations of continuous multispan girder with spring supports based on the displacement method.

Chapter four

Calculations made with the developed cable-stayed bridge analysis methodology have been verified by traditional means – the finite element method. Used calculation software LIRA takes into account the geometrical and physical non-linearity effects. It gives results for some specific points, respectively, for some specific combinations of system input parameters.

Verification was done for the points, which in the third chapter were found to be optimal for certain test criteria.

Bending moments in the stiffness girder, displacements of typical points and tensile forces in cables were verified. In all cases good similarity with the results of the new methodology has been found.

In case of deductive calculation, it is necessary at the beginning of problem solving for flexible supports modelled at cable anchorpoints to assume the spring coefficients, which are nonlinearly dependent on the deformations at the final position. It has been proposed to make this assumption, considering that cables will be loaded up to 1/3 of the allowable stress. The calculation has been repeated with other cable loading ratios (actual stress ratio to the breaking value, which essentially represents a safety factor) and it was found that proposed assumption gives accurate results, as nonlinear effect in actual expected tension range is not significant (error did not exceed 4% in the examined example).

Chapter five

Examples examined in the Doctoral Thesis illustrate possibilities of the newly developed analytical methodology when selecting rational input parameters for cable-stayed bridges.

The ambitious goal set is to incorporate the new method into calculation software, which will allow easy analysis of cable-stayed bridge two-dimensional models, and reasonably choose parameters that simultaneously are economical and also provide the essential criteria of the structure's load bearing capacity, durability and reliability.

The block diagram is provided, how to use the theoretical basis for the approbation of both analysis directions in the software:

- inductive analysis that shows the impact of test criteria on the required input parameters;
- deductive analysis that shows the impact of input parameter on the verifiable criteria.

In both cases the impact is a functional relationship, which is continuous and differentiable function and thus applicable to the mathematical analysis processing (location of extreme points, evaluation of impact "sensitivity", determination of criterion change rate, etc.) and suitable for visual assessment using resulting graphs.

In some cases, it is easily possible to construct influence lines and from their integrated values – internal force envelopes.

CONCLUSION

The Doctoral Thesis developed a new cable-stay bridge load-bearing element interaction analysis method that helps to find rational input parameters of the cable system. Innovative "active" cable system principles have been defined. Application possibilities of the new method are shown with examples. The accuracy of results is verified with traditional methods of calculation.

1) It has been proven that by reducing the stiffness girder's moment of inertia, it is possible to reduce cable cross-sectional area without changing bending moment diagram of the stiffness girder. The value to which it is possible to reduce the cross sectional parameters is determined by the allowable stresses in the optimized construction (ultimate limit state) and displacement restrictions (serviceability limit state).
2) The smallest theoretically possible bending moments of the stiffness girder from variable moving loads can be achieved by creating an "active" cable system – a system that acts as a mechanism applying tension to separate

cables depending on actual displacement of anchorpoints under moving load.

3) „The "active" cable systems ability to reduce the stress of stiffness girder is higher in the structures with a smaller value of the parameter η, which shows the ratio of force generated by the permanent loads to the maximum force, resulting from the most unfavourable variable load location. If the "active" cable system is used to reduce maximum force in the stiffness girder by 10%, then the maximum tensile force in cables increases by 3%. The "active" cable system enables material savings, as well as it is extending life of the structure by reducing the stress fluctuations of the bridge span structure.
4) It has been proven that adjusting mechanism of the "active" cable system shall simultaneously operate only in those cables that include a bridge part (panel) on which the moving load is located, as well as the side cables. This means that the side cables are active continuously, but operation of all other cables is transitory; therefore in case of "active" system, greater safety factors are advisable for the side cables.
5) It has been found that tension forces of cables are proportional to the movements of elastic spring supports. These values are bound by the spring coefficient, which is non-linearly dependent on the stiffness of cable E_vF. It has been verified that within allowable region of bridge deformations the linearization of this correlation using developed methodology produces an error which does not exceed 1.3%.
6) Rational division of stiffness girder into panels and associated placement of cable anchorpoints helps to reduce the maximum tension stresses in the stiffness girder, and also equates tensile forces in cables.