ANALIZA STABILNOSTI NEKIH IZVEDENIH KABLOVSKIH REŠETAKA

STABILITY ANALYSIS OF SOME CONSTRUCTED CABLE TRUSSES

Dragan KOSTIĆ
Vuk MILOŠEVIĆ

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1 KONSTRUKCIJSKE KARAKTERISTIKE NEKIH IZVEDENIH KABLOVSKIH REŠETAKA I CILJ ISTRAŽIVANJA

Izgradnja stadiona za zimske sportove, 1956. godine, u Johaneshovu kod Stokholma u Švedskoj, koji je pokriven kablovskim rešetkama, dovela je do masovne primene ovih konstrukcija [4–11]. Tako je u periodu od nekoliko godina izgrađeno više od stotinu objekata koji su pokriveni ovim konstrukcijskim sistemom. Objekti čije su karakteristike prikazane u Tabeli 1 izabrani su kao tipični primeri kablovskih rešetaka za pokrivanje raspona koji se kreću od 60 m do 80 m, s lakim krovim pokrivačem. U Tabeli 1 date su konstrukcijske šeme, konfiguracije nosača, raspon i dužina objekta, međusobni razmak kablovskih rešetaka, način njihovog oslanjanja i opterećenja [2, 6, 9, 11, 12, 14, 16]. Originalni metod proračuna prikazanih objekata bio je analitički, osim za sportski kompleks „Zdravlje“ u Leskovcu, gde je primenjen Transient Stiffness Method.

Cilj ovog istraživanja jeste dokazivanje ispunjenosti kriterijuma stabilnosti kablovskih rešetaka. Neki od kriterijuma stabilnosti izvedeni su nakon izgradnje analiziranih objekata [1, 12, 13]. Metodologija dokazivanja zasniva se na primeni prikladne metode proračuna za opterećenja koja su korišćena prilikom projektovanja analiziranih konstrukcija.

Dobijeni rezultati proračuna (pomeranja i sile u štapovima) biće analizirani iz aspekta tačnosti, u odnosu na dostupne podatke u vreme projektovanja i zadovoljenja kriterijuma stabilnosti, utvrđivanje nivoa prednaprezanja - uvođenje početne sile zatezanja u kablovski nosač i donošenje zaključaka u pogledu potrebnih minimalnih sila, odnosno potrebe da se eventualno izvrši

1 CONSTRUCTION CHARACTERISTICS OF SOME DERIVED CABLE TRUSSES AND THE AIM OF THE RESEARCH

After the stadium for winter sports, which was covered with cable truss structure, was constructed in Johaneshov near Stockholm in Sweden in 1956, cable trusses have become widely used while constructing such buildings [4-11]. Thus, within several years, more than a hundred buildings were covered using this construction system. The buildings whose characteristics are shown in Table 1 were chosen as typical examples of cable trusses for covering spans from 60 to 80 meters using light roofs. Table 1 presents the construction schemes, the configuration of girders, the span and the length of the buildings, the spaces between the cable trusses, the way of their supporting and loading [2, 6, 9, 11, 12, 14, 16]. The original calculation method of the shown buildings was analytical except for the Sports complex „Zdravlje“ in Leskovac where Transient Stiffness Method was used.

The aim of this research is to prove the fulfilment of stability criteria of cable trusses. Some of the stability criteria were derived after the construction of the analysed buildings [1, 12, 13]. The methodology of proving is based on applying an appropriate calculation method for the particular loadings that were used in the design process of the analysed structures.

The results which were obtained through the calculations (displacements and forces in cable members) are going to be analysed from the point of view of their accuracy in relation to the data available at their constructing time as well as the fulfilment of stability criteria, estimating the level of prestressing - the introdu-

Dragan Kostić, dr, v.prof., Građevinsko-arhitektonski fakultet Univerziteta u Nišu, dragan.kostic@gaf.ni.ac.rs
Vuk Milošević, m.i.a., asistent, Građevinsko-arhitektonski fakultet Univerziteta u Nišu, vukamer@yahoo.com

Dragan Kostić, dr, v.prof., University of Nis, Faculty of Civil Engineering and Architecture, dragan.kostic@gaf.ni.ac.rs
Vuk Milošević, m.i.a., asistent, University of Nis, Faculty of Civil Engineering and Architecture, vukamer@yahoo.com

korekcija unetih sila i do koje mere - u pogledu statičke stabilnosti. Posebno će biti posvećena pažnja proveru kriterijuma stabilnosti kablovskih rešetaka, koji su izvedeni nakon izgradnje analiziranih objekata.

ction of the initial stressing force into the cable girder and drawing conclusions concerning the necessary minimum forces, or the need to make any corrections of the introduced forces and up to which level concerning its static stability. Special attention will be paid to checking stability criteria of cable trusses which were derived after the construction of the analyzed buildings

Slika 1. Prva kablovska rešetka izrađena 1956. godine – Pokriveno klizalište u Johaneshovu kod Stokholma (Švedska), konstruktor Dawid Jawert

Figure 1. The first cable truss constructed in 1956-Roof of Ice Skate Rink in Johaneshov near Stockholm in Sweden Structural engineer David Jawert

2 KRITERIJUMI STABILNOSTI

U vreme gradnje objekata koji su analizirani u ovom radu, korišćeni su kriterijumi stabilnosti koji nisu bili definisani posebnom regulativom za kablovske krovne konstrukcije, već su primenjivane preporuke projektanta i istraživača koji su u tom periodu radili na razvoju modela proračuna (Jawert, Nowitcki, Sobotka) i njegove primene u praksi [11, 14, 17, 18]. U tom periodu, korišćena je analitička metoda za utvrđivanje sila u štapovima i pomeranja, što je u matematičkom pogledu bio dosta složen zadatak. Tadašnji kriterijumi stabilnosti bili su ograničeni na statičke parametre [11, 14, 18]:

(1) Maksimalna dozvoljena vertikalna pomeranja konstrukcije ne smeju biti veća od dozvoljenih ($L/250$);

(2) Nijedan od pojasnih kablovskih elemenata ne sme biti nenapregnut, tj. kablovski elementi u svim fazama opterećenja moraju biti zategnuti;

(3) Efektivna projektna jačina kabla mora biti jednaka najvećim vrednostima sila u kablovima koje nastaju pod uticajem različitih kombinacija opterećenja, ili veća od njih.

Razvojem numeričkih metoda i postupaka proračuna primenom matrične analize za geometrijski nelinearne strukture u elastičnoj oblasti, povećala se preciznost proračuna i pooštrili su se uslovi koje kablovska krovna konstrukcija treba da ispuni kako bi se smatrala stabilnom [3, 12–14].

2 STABILITY CRITERIA

At the period of time when the structures analysed in this paper were constructed, the stability criteria which were used had not been defined by special regulation which would deal with cable roof construction. The recommendations of their constructors or researchers who were working on developing calculation models and their application in practice were often used; some of them were Jawert, Nowitcki and Sobotka. [11, 14, 17, 18]. At that period of time analytical method for obtaining the forces in cable members and movements was used. It was a rather complex task from mathematical point of view. Stability criteria at that time were limited to static parameters. [11, 14, 18]

(1) Maximum allowed vertical displacements of a structure must not be larger than the allowed ones ($L/250$),

(2) None of the main cable elements couldn't be unstressed, i.e. cable elements must be stressed in each of the loading phases,

(3) The effective designed cable strength must be equal or larger than the largest force values in the cables resulting from the influence of different loading combinations

After the development of numerical methods and the improvement of calculation procedures using matrix analysis for geometrically nonlinear structures in the elastic area the precision of calculations was increased and the criteria which must be fulfilled by cable roof con-

a) Standardizovani žičani kablovi: zaštićeni protiv korozije, relaksirani, sa ugrađenim odgovarajućim završnim elementima i spojnica;

b) Efektivna projektna jačina kabla mora biti jednaka ili veća od najveće vrednosti sila u kablovima koje nastaju pod uticajem različitih kombinacija opterećenja, multiplikovana odgovarajućom konstantom [2];

c) Maksimalna dozvoljena pomeranja konstrukcije ne smeju biti veća od propisanih [3,14];

d) Nijedan od kablovskih elemenata ne sme biti nenapregnut, tj. kablovski elementi u svim fazama opterećenja moraju biti zategnuti [3,14];

e) Uslovi za postizanje rezonance ili kvazirezonance, koji dovode do velikih deformacija, moraju se izbeći u slučaju da viseći krovovi budu izloženi dinamičkim opterećenjima (vetar, eksplozija ili zemljotres) [3, 14].

3 PREGLED METODA PRORAČUNA

Za razliku od jednostavnijih konstruktivnih sistema, kablovske rešetke karakteriše nelinearno ponašanje koje nije uzeto u obzir kod uobičajenih metoda proračuna. Zbog toga su uvedene neke nove metode koje uzimaju u obzir geometrijsku nelinearnost kablovskih rešetaka. Najprimenjivnije metode su force density metoda, dynamic relaxation metoda i transient stiffness metoda [15]. One će biti detaljnije objašnjene.

3.1 Force density metoda

Ova metoda nastala je sredinom prošlog veka, zajedno s prvim značajnijim objektima izgrađenim u sistemu kablovskih struktura. Osnovna pretpostavka je prilično jednostavna - odnos intenziteta sile zatezanja u svakom elementu, odnosno kابلu, i dužine elementa jeste konstantan. Po ovom odnosu metoda je i dobila ime, jer u bukvalnom prevodu znači „gustina sile”. Koristeći ovu pretpostavku, sistem jednačina koji opisuje geometriju strukture svodi se na linearan sistem u kome su nepoznate samo pomeranja čvorova. Ovakav sistem može se rešiti i ručno kada nema veliki broj elemenata, ali se za uobičajene konstrukcije uvek koriste računari zbog bržeg i tačnijeg proračuna. Kao konačan rezultat dobija se ravnotežna geometrija sistema štapova. Odnos intenziteta sile zatezanja u kابلu i dužine kabla neophodno je pretpostaviti. On može biti različit za različite kablove. Ukoliko se ovaj odnos proporcionalno promeni za sve kablove, neće se promeniti geometrija, već samo intenzitet sila u kablovima.

structions in order to be considered stable were more strictly defined [3, 12-14].

a) Standardized wire cables: protected against corrosion, stress relaxed, with the inbuilt appropriate support elements and connectors,

b) Effective projection cable strength must be equal or larger than the largest force values in the cables resulting from the influence of different loading combinations multiplied by an appropriate constant value [2],

c) Maximum allowed movements of a structure must not be larger than those defined by technical regulations [3, 14];

d) None of the cable elements must be unstressed, i.e. cable elements must be stressed in each of the loading phases [3, 14]

e) The conditions for obtaining resonance or the so-called resonance which cause large deformities must be avoided in the cases when hanging roofs are exposed to dynamic loadings (wind, explosion or earthquake) [3, 14].

3 CALCULATION METHODS SURVEY

Since cable trusses differ from other simple construction systems they are characterized by nonlinear behaviour which was not taken into account while common calculations methods were used. That was the reason for introducing some new methods which take into account geometrical nonlinearity of cable trusses. The methods which were mostly used are Force Density Method, Dynamic Relaxation Method and Transient Stiffness Method [15]. They will be explained in more detail.

3.1 Force Density Method

This method was established in the middle of the 20th century at the same time when the first important buildings with cable trusses systems were constructed. The basic presumption is rather simple and it states that the ratio of the stressing force in each of the elements, i.e. cables and of the element's length is a constant one. The method itself got its name after the word 'ratio', because if translated literally it means 'the density of forces'. Using this presumption, the system of equations which describes geometry of the structure can be derived to a linear system in which only the nodes transitions are unknown. This kind of system can be easily calculated without using computers if the number of elements is not a large one. However, computers are always used for common constructions because the calculation is faster and more accurate. As the final result we get equilibrium geometry of the system of rods. The ratio between the intensity of the prestressing force in a cable and the length of a cable must be assumed. It can be different for different cables. If this ratio is proportionally changed for all of the cables the geometry will not change. Only the intensity of forces in cables will change.

Tabela 1. Konstrukcijske karakteristike nekih kablovskih rešetaka
Table 1. Structural properties of some constructed cable trusses

Objekat Structures	Sportska hala u Bilinghemu, Engleska Sports Hall in Bellingham (England) [14]	Prolazni magacin u Šipholu, Holandija Transitory Warehouse in Shiphal (the Netherlands) [14]	Ledena dvorana u Johaneshovu, Švedska The Ice Rink Hall in Johaneshov (Sweden) [14]	Sportski kompleks „Zdravlje” u Leskovcu, Srbija Sports complex “Zdravlje” in Leskovac (Serbia) [2, 12]
Shema Chart (Scheme)				
Međusobni razmak nosača Distance of girders	3.35 m	4.7 m	5.28 m	5.0 m
Dužina objekta Length of structures	40 m	140 m	120 m	45 m
Tip oslonake konstrukcije Supporting structure	Izvrnuti luk Inverted arch	Čelični stubovi i zatege Steel columns and stay cables	Čelični stubovi i zatege Steel columns and stay cables	AB stubovi i čelične zatege RC columns and steel ties
Broj čvorova konstrukcije Number of nodes	19	19	19	24
Slobodni/oslonaki čvorovi Free/support nodes	15 / 4	15 / 4	15 / 4	18 / 6
Broj štapova Number of members	30	30	32	35
Noseći/dijag./stabilizujući carrying / diagonal / prestressing	10 / 12 / 8	10 / 12 / 8	10 / 14 / 8	10 / 15 / 10
Površine poprečnih preseka area of cross section	1000 / 400 / 446 mm ²	1520 / 400 / 594 mm ²	2325 / 600 / 1592 mm ²	1511 / 381 / 400 mm ²
Prednaprezanje (ekvivalent) Prestress (equivalent)	0.28 kN/m ²	0.20 kN/m ²	0.39 kN/m ²	0.15 kN/m ²
Opterećenja kN/m ² Load kN/m ²				
g = sopstvena težina/ self weight	0.40	0.50	0.42	0.35
s = sneg/ snow	0.75	0.50	1.00	1.00
w = vetar/wind	-0.60	-0.42	-0.40	-0.64
t = temperatura °C/temperature oC	-20 do +20	-10 do +25	-20 do +20	-15 do +15
Pomeranja u odnosu na projektovani položaj Displacement from designed position; m				
s = sneg/snow	0.530	0.400	0.430	0.204
w = vetar/wind	-0.280	-0.310	-0.180	-0.142

3.2 Dynamic relaxation metoda

Ova metoda razvijena je u isto vreme kada i force density metoda. Koristi se za analizu kablovskih struktura, kao i drugih tipova konstrukcija. Metoda se zasniva na diskretizaciji prostora i koncentrisanju masa u čvorovima diskretizovane mreže. Ovakav sistem osciluje pod dejstvom opterećenja dok ne dođe do stanja mirovanja izazvanog prigušenjem koje se javlja u sistemu. Primenjuju se dve vrste prigušenja: viskozno i kinetičko. U slučaju viskoznih prigušenja treba pretpostaviti koeficijent prigušenja prema postojećim smernicama. Pogrešan odabir vrednosti ovog koeficijenta dovodi do sporije konvergencije i produžava proces nalaženja ravnotežne geometrije sistema. U slučaju kinetičkog prigušenja primenjuje se iterativni postupak koji u konačnom dovodi do toga da rezidualne sile teže nuli, odnosno da sistem dolazi u ravnotežnu geometriju.

3.3 Transient stiffness metoda

Ova metoda nastala je razvojem metoda koje imaju pretpostavku malih pomeranja, odnosno uzimaju u obzir geometrijski nelinearno ponašanje konstrukcija. Sama metoda je nelinearna. Matematički, problem se formuliše u vidu sistema linearnih algebarskih jednačina, koji se uspešno rešava primenom Njutn-Rafsonove metode - iterativnim postupkom¹. Postupak rešavanja sistema jednačina ponavlja se sve dok vektor, koji predstavlja deo neuravnoteženog opterećenja u svim čvorovima sistema, ne bude jednak nuli ili se ne svede na približno dovoljno malu vrednost, koja bitno ne utiče na željenu tačnost rezultata.

Metoda primenjuje seriju koraka u kojima se izračunavaju pomeranja, pri čemu se u svakom narednom koraku menja matrica krutosti. Otuda i naziv metode koji u bukvalnom prevodu znači metoda kratkotrajnih ili trenutnih krutosti. Postupak promene matrice krutosti nastavlja se dok rezidualne sile ne postanu bliske nuli. U poređenju s dynamic relaxation metodom, transient stiffness metoda dolazi do ravnotežne geometrije putem manjeg broja iteracija, ali je zato trajanje tih iteracija duže.

Osnovni problem u proračunu ovim postupkom jeste kako da se pretpostave ulazni podaci za „početni” tzv. referentni položaj (sile i geometrija), imajući u vidu da u štapovima konstrukcije deluju sile, iako na nju ne deluje spoljašnje opterećenje. Za pretpostavljene sile i geometriju, sistem treba da je u ravnoteži.

¹Svaki iterativni postupak podrazumeva aproksimaciju - pretpostavku početnih, ulaznih podataka

3.2 Dynamic Relaxation Method

This method was also made at the same time when the Force Density Method was made. It is used both for analyzing cable structures and for analysing other types of constructions. The method is based on the discretization of space as well as on the concentration of masses in the nodes of the discrete truss. A system like this oscillates under the influence of loading until it reaches the state of lull caused by the suppression that occurs in the system. Two kinds of suppression are applied: viscous and kinetic. In viscous suppressions it is necessary to presume the coefficient of suppression according to the already existing directions. Choosing wrong values of this coefficient results in a slower convergence and makes the process of finding the equilibrium of systems' geometry much longer. Iterative procedure is used in kinetic suppression and it finally leads to the fact that the residual forces tend to equal zero, and the system reaches geometrical equilibrium.

3.3 Transient Stiffness Method

This method was being made together with the development of the methods which were based on the presumption of small displacements, i.e. the methods which take into account geometrically nonlinear behaviour of structures. The method itself is nonlinear. Mathematically speaking, the problem is defined as a system of linear algebraic equations which can easily be solved using Newton-Raphson's method the iterative procedure. The procedure of solving the equations is repeated until the vector which represents a part of unbalanced loading in all system's nodes equals zero or reaches the value which is so small that it cannot significantly influence the sought accuracy of results.

This method consists of a series of steps through which transitions are calculated and in each further step the matrix of stiffness is changed. That is why it got its name similar to its literal translation meaning short term or temporary stiffness. The procedure of changing the matrix of stiffness is continued until the residual forces reach approximately zero. When compared to Dynamic Relaxation Method, Transient Stiffness Method obtains equilibrium geometry using a smaller number of iterations but the time of iterations is longer.

The basic problem while using this procedure is how to predict the input data for the 'initial', the so called referential position (forces and geometry) having in mind that there are forces which are present in construction rods although itself it is unaffected by any external loading. For the predicted forces and geometry the system should be in equilibrium position.

3.4 Analitička metoda

Ova metoda upotrebljena je za proračun krovnih nosača na objektima u Johaneshovu [11], Shipholu [14] i Bilinghemu [14]. Zasniva se na korišćenju uslova ravnoteže i promene dužina lančanica pri opterećenju, formiraju se sistemi nelinearnih diferencijalnih jednačina [4–6, 9]. Ovaj način je prilično komplikovan, ako se ne uvedu uprošćenja u postavci problema (npr. kablovska rešetka se posmatra kao neprekidna glatka površ-membrana, opterećenje je vertikalno, ravnomerno raspodeljeno, lančanica je gipka i plitka, ima oblik parabole, oslonci su nepomerljivi, kablovi su idealno elastični). Uprošćenjima i aproksimacijama eliminišu se male veličine višeg reda, pa se linearizuje sistem diferencijalnih jednačina i svodi na lako rešiv problem sa očekivanom greškom od 6% do 10%.

3.5 Kombinovana analitičko-numerička metoda

Osim primene analitičkih i numeričkih metoda, postoji i mogućnost njihove kombinacije. I analitičke i numeričke metode imaju svojih prednosti i mana. Numeričke metode brže rešavaju problem od analitičkih metoda, te dolaze do ravnotežne geometrije sistema kablovske rešetke, ali zato zahtevaju pretpostavljanje ulaznih parametara. Pretpostavljanje ulaznih parametara veoma je važno jer utiče na brzinu proračuna. Jedan od ključnih ulaznih parametara jeste intenzitet sile prednaprezanja u kablovima, jer od njega umnogome zavisi stabilnost same rešetke. Postoje preporuke koje se tiču intenziteta sile prednaprezanja u kablovima koje bi trebalo da olakšaju pretpostavljanje ovog ulaznog parametra, međutim, postojeće preporuke nisu dovoljno precizno definisane. To za posledicu najčešće ima nedovoljnu zategnutost konstrukcije koja uzrokuje neispunjavanje postojećih kriterijuma stabilnosti. Zato se postupak mora ponavljati iz početka s većim pretpostavljenim intenzitetom sile u kablovima. Ovo ponavljanje dovodi do neželjenog produžavanja ukupnog vremena proračuna, i zato je bilo neophodno naći način da se ceo postupak optimizuje.

Rešenje je pronađeno upravo u kombinaciji numeričkih metoda sa analitičkim. Na ovaj način, koriste se prednosti obe vrste metoda, dok se njihovi nedostaci minimiziraju. Konkretno, analitička metoda koristi se za dobijanje ulaznih parametara za numeričku metodu. Time se izbegava pretpostavljanje parametara, jer ono može biti neprecizno i omogućava nestabilnost konstrukcije koja je vidljiva tek na kraju proračuna. S druge strane, nedostaci primene samo analitičke metode ogledaju se u dužem vremenu proračuna i grešci koja se javlja u rezultatima usled aproksimacija i eliminacije malih veličina višeg reda. Primena računara rešava problem dugog analitičkog proračuna, dok kombinacija s numeričkim metodom smanjuje greške u rezultatima. Kao najpodesnija metodologija za proračun kablovskih rešetaka izabrana je kombinacija analitičkog i numeričkog transient stiffness metoda [12,13]. Već je pomenuto da su pretpostavljanje geometrije i intenziteta prednaprezanja najveći problem transient stiffness metode. Kombinacija sa analitičkim metodom rešava ne samo problem intenziteta prednaprezanja, već i

3.4 Analytical Method

This method was used for calculating roof girders on the buildings in Johaneshov [11], Shiphol [14], and Bilinghem [14]. It is based on using the equilibrium conditions and the change in catenary lengths while loading it. Systems of nonlinear differential equations are formed [4-6, 9].

This procedure is rather complicated if no simplifications are introduced in defining the problem, (for example a cable truss is regarded to be a continuous plane surface - a membrane, loading is vertical, equally distributed, the catenary is elastic and shallow in the shape of a parable, support points are immovable, cables are ideally elastic...) Simplifications and approximations eliminate small values of a higher rank and lead to a system of differential equations reducing it to a problem that can be solved; the expected error can be from 6% up to 10%.

3.5 Combined analytical-numerical method

Besides being used separately, analytical and numerical methods can be combined. Both analytical and numerical methods have their advantages and disadvantages. The use of numerical methods, if compared to the analytical ones, solve problems more quickly and reach the equilibrium geometry of the cable truss system, but at the same time they require the prediction of the input parameters. The process of predicting the input parameters is very important because it influences the speed of calculation. The intensity of the prestressing forces in cables is one of the most important input parameters, because the stability of a truss itself depends upon it. There are some recommendations concerning the intensity of prestressing forces in cables which could make predicting this input parameter easier, however the already existing recommendations are not defined enough precisely. It causes an inadequate level of construction's stressing leading to the lack of fulfilment of the already existing stability criteria. Thus, the process must be repeated from the very beginning and the prediction of a larger intensity of the forces in cables must be made. This repetition makes the time necessary for completing the calculation much longer and it was necessary to elaborate a new method in order to make the process more adequate.

The situation was resolved by combining the numerical method with the analytical one. In this way it is possible to combine the advantages of both methods and to make their disadvantages less frequent. Precisely speaking, the analytical method is used for obtaining the input parameters necessary for the numerical method. In this way it is possible to avoid predicting parameters because it can be imprecise and lead to construction's instability which is obvious only at the end of the calculation. On the other hand, the shortcomings of using the analytical method only are longer period of calculation time and elimination of small values of higher rank. The use of computers solves the problem of long analytical calculation, while its combination with numerical method lessens the mistakes in results. This combination of the analytical and numerical method was chosen as the most appropriate one for calculating cable

geometriju sistema kablovske rešetke. Za dobijanje referentnog položaja korišćen je modifikovan postupak profesora Balgača [4, 5, 6]. Modifikacija ovog postupka ogledala se u tome što je on prilagođen primeni na računaru i primeni na kablovske rešetke. Istovremeno, određeni elementi proračuna su uopšteni, te je na taj način omogućena njegova primena i na neke druge tipove konstrukcija. Ovako modifikovan postupak profesora Balgača daje izuzetno tačne rezultate za početni položaj sistema i to pri veoma kratkom vremenu proračuna. Glavni uslov za stabilnost prema postupku profesora Balgača jeste postojanje sile kontakta „v”. Sila kontakta je vertikalna komponenta sile kojom prednaprežući kabl opterećuje noseći. Postojanje sile kontakta prema Balgaču znači da ona mora da postoji i u najnepovoljnijem slučaju opterećenja. Drugim rečima, prednaprežući kabl uvek mora da opterećuje noseći kako bi kablovska rešetka bila stabilna.

Primena kombinovanog analitičko-numeričkog metoda uslovljena je primenom računara odnosno originalnog¹ softvera „Cabl”, prema blok-šemi datoj na Slici 2. Softver „Cabl” sadrži tri programske celine: „Cabl-T” (modul koji koristi analitičku metodu), „Cabl-TP” (modul koji povezuje analitički dobijene rezultate s modulom koji će ih koristiti kao početne u iterativnom postupku po numeričkoj Transient Stiffness Method) i „Cabl-N” (numerički modul-Transient Stiffness Method).

4 KONTROLA RAVNOTEŽE KABLOVSKIH REŠETAKA U REFERENTNOM POLOŽAJU TRANSIENT STIFFNESS METODOM

Za gore definisane konstrukcije prethodno napregnutih kablovskih rešetaka obešenog krova, izvršena je provera ravnoteže u referentnom položaju (faza potpunog prethodnog naprezanja)[12,13,19]. Pritom, na sistem ne deluje spoljašnje opterećenje. Parametri referentnog položaja: koordinate čvorova i sile u štapovima dobijeni su primenom programa **CABL-T** po metodi prof. Balgača, koja je prilagođena za kablovske rešetke i programski prilagođena za računarsku primenu. Programom **CABL-TP** formirana je ulazna datoteka za transient stiffness metod, tj. definisana konfiguracija sistema: numeracija čvorova, povezivanje štapova, opterećenje i temperaturna promena u štapovima, a za preuzete podatke iz programa CABL-T.

Podaci dobijeni programom CABL-T predstavljaju ravnotežno stanje konstrukcije u referentnom položaju, a dobijeni su analitičkim postupkom prof. Balgača. Transient stiffness metodom, tj. programom **CABL-N**, kontrolisana je ravnoteža sistema, prema blok-šemi postupka proračuna [1] prikazanoj na Slici 2. Dobijeni rezultati

trusses [12, 13]. We have already mentioned that the prediction of geometry and the intensity of prestressing is the biggest problem of the Transient Stiffness Method. The combination with the analytical method solves both the problem of the intensity of prestressing and geometry of a cable truss. Modified procedure of professor Balgacs [4, 5, 6] was used for obtaining the referential position. The modification of the procedure consisted in the fact that it was adapted to computer use and application on cable trusses. At the same time some of the calculation elements were generalized and in that way it was made possible to use it on some other construction types. This modified procedure of professor Balgacs gives very accurate results for the initial position of system after a very short time of calculation. The most important condition for stability, according to professor Balgacs's procedure, is the presence of the contact force 'v'. The contact force is a vertical component of force through which a prestressing cable loads the carrying one. According to professor Balgacs, the presence of the contact force means that it also must be present in the most unfavourable loading situation. In other words, the prestressing cable must always load the carrying one to ensure the stability of the cable truss.

The use of the combined analytical-numerical method is conditioned by the use of PC, actually the original software¹ "Cabl" according to the block-scheme given in Figure 2. The software "Cabl" consists of three programme units: "Cabl-T" (the module uses the analytical method), "Cabl-TP" (the module connects the results which were analytically obtained to the module which is going to use them as the initial ones in the iterative procedure while applying the numerical Transient Stiffness Method), and "Cabl -N" (numerical module-Transient Stiffness Method).

4 CONTROLLING THE EQUILIBRIUM OF CABLE TRUSSES IN THE REFERENTIAL POSITION USING TRANSIENT STIFFNESS METHOD

The control of the equilibrium in the referential position was done for the already mentioned structures since they consist of the prestressed cable trusses of hanged roofs (the phase of complete prestressing) [12, 13, 19]. In this case the system is uninfluenced by external loading. The parameters of the referential position: nodes coordination and forces in members are obtained using the programme "**CABL-T**" according to professor Balgac's method which was adapted both for cable trusses and as a programme for computer use. The input data base for the Transient stiffness Method was obtained through the use of programme "**CABL-TP**" i.e. the configuration of the system was defined: nodes numeration, connection of rods, loading and temperature changes in cable members for the data overtaken from programme "Cabl-T".

The data obtained through CABL-T represent the equilibrium state of the construction in the referential position obtained using the analytical procedure of professor Balgac. Through the use of Transient Stiffness

¹ Autor softvera „Cabl” je prvopotpisani autor ovog rada

¹ Author of the software "Cable" is the first signed author of this paper

Slika 2. Blok-šema algoritma analitičko-numeričkog proračuna prethodno napregnutih kablovskih struktura

Figure 2. Block diagram of the algorithm of analytical and numerical calculation method for prestressed cable structures

složeni su tabelarno. Zbog preglednosti rezultata, prikazane su samo maksimalne vrednosti pomeranja i sila u pojasnim štapovima:

– Maksimalna korekcija vertikalnih koordinata slobodnih čvorova sistema (Tabela 2). Horizontalna pomeranja su zanemarljivo mala.

– Ukupne sile u štapovima i njihove korekcije (Tabela 3). U sistemu ne postoje nenapregnuti (labavi) stapovi u referentnom položaju.

Method, i.e. the programme **CABL-N** we controlled the equilibrium of the system according to the block-scheme of the calculation procedure [1] shown in *picture 2*. The obtained data are classified in tables. Only the maximum values of movements and the forces in cable members are shown because of an easy survey.

– Maximum correction of vertical coordinates of the system's free nodes (Table 2) Horizontal movements are insignificantly small

– All of the forces in members and their corrections (Table 3). The system does not include unstressed (loose) members in referential position.

Tabela 2. Maksimalna korekcija pomeranja slobodnih čvorova sistema u referentnom položaju – čvor u sredini raspona
Table 2. The maximum displacement correction of free nodes in the reference position - the node in the middle of span

Vertikalni položaj čvora dobijen programom Vertical position of the node obtained from program	Sportska hala u Bilinghemu, Engleska Sports Hall in Bellingham (England)	Prolazni magacin u Šipholu, Holandija Transitory Warehouse in Shiphall (the Netherlands)	Ledena dvorana u Johaneshovu, Švedska The Ice Rink Hall in Johaneshov (Sweden)	Sportski kompleks „Zdravlje” u Leskovcu, Srbija Sports complex “Zdravlje” in Leskovac (Serbia)
CABL-T	4,597 m	4,819 m	4,349 m	4,017 m
CABL-N	4,586 m	4,805 m	4,334 m	3,999 m
Korekcija Correction	1,13 cm	1,36 cm	1,46 cm	1,82 cm
Odstupanje Deviation	2,5 ‰	2,8 ‰	3,4 ‰	4,48 ‰

Tabela 3. Maksimalna korekcija sila u pojasnim štapovima sistema u referentnom položaju
Table 3. The maximum force corrections in cable members in reference position

Vertikalni položaj čvora dobijen programom Force obtained from the program		Sportska hala u Bilinghemu, Engleska Sports Hall in Bellingham (England)	Prolazni magacin u Šipholu, Holandija Transitory Warehouse in Shiphall (the Netherlands)	Ledena dvorana u Johaneshovu, Švedska The Ice Rink Hall in Johaneshov (Sweden)	Sportski kompleks „Zdravlje” u Leskovcu, Srbija Sports complex “Zdravlje” in Leskovac (Serbia)
Gornji-noseći kabl Carrying cable	CABL-T	402,770 kN	617,048 kN	929,168 kN	249,288 kN
	CABL-N	418,751 kN	637,592 kN	966,349 kN	265,722 kN
	Korekcija Correction	15,981 kN	20,544 kN	37,181 kN	16,434 kN
	Odstupanje Deviation	3,82 %	3,22 %	3,85 %	6,18 %
Donji-stabilizujući kabl Prestressing cable	CABL-T	298,992 kN	408,463 kN	908,391 kN	237,074 kN
	CABL-N	293,004 kN	400,515 kN	891,884 kN	239,076 kN
	Korekcija Correction	-5,988 kN	-7,948 kN	-16,508 kN	-3,002 kN
	Odstupanje Deviation	2,05 %	1,98 %	1,85 %	1,26 %

4.1 Diskusija na osnovu rezultata

Očigledna je opravdanost primene predložene metode za pribavljanje početnih parametara za konačan proračun prethodno napregnutih kablovskih struktura po transient stiffness metodi.

4.1 The discussion of the results

The necessity to use the already suggested method for obtaining the initial parameters for the final calculation of prestressed cable structures according to Transient Stiffness Method is obvious.

Neznatne su korekcije geometrije tačaka sistema, a takođe i sila u štapovima. Maksimalne korekcije geometrije su: 1.13 cm, 1.36 cm, 1.46 cm i 1.82 cm. Maksimalne korekcije sila u štapovima nosećeg kabla jesu: 3,22% do 6,18% u odnosu na silu dobijenu transient stiffness metodom, dok su korekcije sila u štapovima stabilizujućeg kabla u granicama 1,26% do 2,05%.

Pretpostavljeni podaci vrlo su bliski ravnotežnom stanju, jer se konačni ravnotežni položaj dobija kroz 3 iteracije programom CABL-N.

5 PRORAČUN KABLOVSKIH REŠETAKA ZA PRORAČUNSKA OPTEREĆENJA TRANSIENT STIFFNESS METODOM

Tipični primeri kablovskih rešetaka za pokrivanje raspona koji se kreću od 60 m do 80 m, s lakim krovnim pokrivačem, analizirani su u prethodnom odeljku iz aspekta opravdanosti primene kombinovane, analitičko-numeričke metode, za dobijanje parametara u referentnom položaju sistema. Proračun analiziranih kablovskih rešetaka za projektovana opterećenja daće nam odgovore konstrukcija, koji će biti analizirani iz aspekta kriterijuma stabilnosti [12,13,19].

Svaka od analiziranih konstrukcija, prvobitno je prethodno napregnuta - sračunati početni parametri po analitičkoj metodi profesora Balgača, koja je prilagođena za primenu na kablovske rešetke i primenu na računaru (programski modul CABL-T). Pretprocesor CABL-TP formirao je ulaznu datoteku za MKP. Programski modul CABL-N, sa opcijom provere ravnoteže za referentni položaj (faza potpunog prednaprezanja), proverom ravnoteže formirao je i novu ulaznu datoteku INPUT.DAT s podacima o svim fazama opterećenja. Opterećenja deluju na uravnoteženu prethodno napregnutu konstrukciju kablovskih rešetaka.

Opterećenja deluju na konstrukcije, kao što je predviđeno tadašnjim projektima (Tabela 1), a sama konstrukcija prolazi kroz sledeće faze opterećenja, koje deluju na prethodno zategnutu stabilnu konstrukciju:

- (1) Sopstvena težina krova i konstrukcije **g**,
- (2) Sopstvena težina krova i konstrukcije i sneg: **g+s**
- (3) Sopstvena težina krova i konstrukcije, sneg i sisajuće dejstvo vetra na celoj površini krova: **g+s-w**
- (4) Sopstvena težina krova i konstrukcije i sisajuće dejstvo vetra na celoj površini krova: **g-w**
- (5) Sopstvena težina krova i konstrukcije i negativna temperaturna promena na štapove sistema **g-t**,
- (6) Sopstvena težina krova i konstrukcije i pozitivna temperaturna promena na štapove sistema **g+t**,
- (7) Sopstvena težina krova i konstrukcije, sneg i negativna temperaturna promena na štapove sistema: **g+s-t**
- (8) Sopstvena težina krova i konstrukcije, sneg i pozitivna temperaturna promena na štapove sistema: **g+s+t**
- (9) Sopstvena težina krova i konstrukcije, sneg, sisajuće dejstvo vetra na celoj površini krova i negativna temperaturna promena na štapove sistema: **g+s-w-t**
- (10) Sopstvena težina krova i konstrukcije, sneg, sisajuće dejstvo vetra na celoj površini krova i pozitivna temperaturna promena na štapove sistema: **g+s-w+t**
- (11) Sopstvena težina krova i konstrukcije, sisajuće dejstvo vetra na celoj površini krova i negativna temperaturna promena na štapove sistema: **g-w-t**
- (12) Sopstvena težina krova i konstrukcije, sisajuće dejstvo vetra na celoj površini krova i pozitivna temperaturna promena na štapove sistema: **g-w+t**

The corrections of the system's geometry points, as well as of the forces in members are insignificant. Maximum corrections of the system's geometry points are: 1.13cm, 1.46cm, and 1.82cm. Maximum corrections of the forces in the carrying cable members are: 3.22%, up to 6.18% if compared to the force obtained through the Transient Stiffness Method; whereas the corrections of the forces in the cable members of the stabilizing cable are 1.26% up to 2.05%.

The predicted data are very close to the equilibrium state since the final equilibrium state is obtained through three iterations using the programme "CABL-N"

5 CABLE TRUSSES CALCULATION FOR THE CALCULATION LOADINGS OF THE TRANSIENT STIFFNESS METHOD

Typical examples of cable trusses for covering spans from 60m to 80m long using light roof coverings have been analyzed in the previous chapter. The analysis dealt with the aspects of the appropriate use of applied combined, analytical-numerical method for obtaining the parameters in the referential position of the system. The calculations of the cable trusses for the projected loadings will show us possible construction responses and they are going to be analyzed concerning the aspects of stability criteria. [12, 13, 19].

Each of the analyzed constructions was prestressed first-the initial parameters were calculated according to the analytical method of professor Balgac which had previously been adapted for the use on cable trusses and the use by computers (programme module "CABL-T"). The preprocessor "CABL-TP" had made the input data file for Transient Stiffness Method. Programme module "CABL-N" with the option for checking the equilibrium in the referential position (the phase of complete prestressing), had made a new input data file INPUT.DAT after having checked the equilibrium and it included the data about all loading phases.

The loadings affect the construction as the present projects predicted (Table 1), and the construction itself goes through the following loading phases which affect the prestressed stable construction:

- (1) The own weight of both the roof and the construction **g**
- (2) The own weight of both the roof and the construction and snow load **g+s**
- (3) The own weight of both the roof and the construction, snow and the sucking effect of the wind on the whole roof surface: **g+s-w**
- (4) The own weight of both the roof and the construction and the sucking effect of the wind on the hole roof surface: **g+w**
- (5) The own weight of both the roof and the construction and the negative temperature change on the system's members **g-t**
- (6) The own weight of both the roof and the construction and the positive temperature change on the system's members **g+t**
- (7) The own weight of both the roof and the construction, snow and the negative temperature change on the system's members: **g+s-t**
- (8) The own weight of both the roof and the construction, snow and the positive temperature change on the system's members: **g+s+t**
- (9) The own weight of both the roof and the construction, snow, sucking effect of the wind on the whole roof surface and the negative temperature change in the system's members: **g**

Karakteristični parametri koji utiču na stabilnost analiziranih kablovskih rešetaka prikazani su u Tabeli 4, za sve karakteristične faze opterećenja.

+s -w-t

(10) The own weight of both the roof and the construction, snow, sucking effect of the wind on the whole roof surface and the positive temperature change in the system's members: **g +s -w + t**

(11) The own weight of both the roof and the construction, sucking effect of the wind on the whole roof surface and negative temperature change in the system's members: **g -w -t**

(12) The own weight of both the roof and the construction, sucking effect of the wind on the whole roof surface and positive temperature change in the system's members: **g -w + t**

Specific parameters that affect the stability of the analyzed cable trusses are shown in Table 4, for all specific loading phases

Tabela 4. Karakteristični parametri koji utiču na stabilnost analiziranih kablovskih rešetaka

	Sportska hala u Bilinghemu, Engleska	Prolazni magacin u Šipholu, Holandija	Ledena dvorana u Johaneshovu, Švedska	Sportski kompleks „Zdravlje” u Leskovcu, Srbija
Referentni položaj	Prednaprezanje			
Projektovani položaj	Prednaprezanje i sopstvena težina krova s konstrukcijom			
(1) faza opterećenja	g			
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	512.328	860.247	1159.645	405.023
Maksimalna sila u stabilizujućem kablu [kN]	276.156	338.104	852.455	210.725
Pomeranja u odnosu na referentni položaj [m]	0.1877	0.3442	0.1874	0.1320
(2) faza opterećenja	g+s			
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	737.163	1118.094	1743.888	888.726
Maksimalna sila u stabilizujućem kablu [kN]	183.646	242.893	651.260	122.844
Pomeranja u odnosu na projektovani položaj [m]	0.3514	0.3493	0.4542	0.2792
(3) faza opterećenja	g+s-w			
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	557.329	901.561	1507.784	581.215
Maksimalna sila u stabilizujućem kablu [kN]	255.994	321.174	751.785	179.239
Pomeranja u odnosu na projektovani položaj [m]	0.0713	0.0523	0.2692	0.1038
(4) faza opterećenja	g-w			
Nenapregnuti štapovi	ne	ne	ne	Neki dijag. ²
Maksimalna sila u nosećem kablu [kN]	402.156	661.550	967.364	194.286
Maksimalna sila u stabilizujućem kablu [kN]	335.104	398.773	911.259	296.851
Pomeranja u odnosu na projektovani položaj [m]	-0.0886	-0.2949	-0.1784	-0.2663
(5) faza opterećenja	g-t			
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	540.863	880.818	1229.884	427.371
Maksimalna sila u stabilizujućem kablu [kN]	297.095	353.324	949.431	230.347
Pomeranja u odnosu na projektovani položaj [m]	-0.0016	-0.0171	-0.0165	-0.0217
(6) faza opterećenja	g+t			
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	484.796	809.471	1090.078	382.892
Maksimalna sila u stabilizujućem kablu [kN]	254.204	299.668	814.646	191.480
Pomeranja u odnosu na projektovani položaj [m]	0.018	-0.0255	0.017	0.0237

(7) faza opterećenja		g+s-t		
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	762.125	1136.690	1804.279	907.484
Maksimalna sila u stabilizujućem kablu [kN]	206.402	258.162	729.567	142.829
Pomeranja u odnosu na projektovani položaj [m]	0.3308	0.3304	0.4293	0.2611
(8) faza opterećenja		g+s+t		
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	712.537	1072.279	1684.366	870.296
Maksimalna sila u stabilizujućem kablu [kN]	160.815	204.597	572.717	102.927
Pomeranja u odnosu na projektovani položaj [m]	0.3723	0.3791	0.4797	0.2973
(9) faza opterećenja		g+s-w-t		
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	584.537	921.784	1571.237	601.161
Maksimalna sila u stabilizujućem kablu [kN]	279.125	336.372	829.982	199.658
Pomeranja u odnosu na projektovani položaj [m]	-0.0531	0.040	0.2467	0.0861
(10) faza opterećenja		g+s-w+t		
Nenapregnuti štapovi	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹	Neki dijag. ¹
Maksimalna sila u nosećem kablu [kN]	530.441	851.665	1445.192	561.676
Maksimalna sila u stabilizujućem kablu [kN]	233.728	283.014	673.351	158.837
Pomeranja u odnosu na projektovani položaj [m]	-0.0899	0.0836	0.2922	0.1214
(11) faza opterećenja		g-w-t		
Nenapregnuti štapovi	Ne	Ne	Ne	Neki dijag. ²
Maksimalna sila u nosećem kablu [kN]	439.825	685.507	1053.807	232.741
Maksimalna sila u stabilizujućem kablu [kN]	355.455	411.798	983.680	320.191
Pomeranja u odnosu na projektovani položaj [m]	-0.3637	-0.3029	-0.1896	-0.2860
(12) faza opterećenja		g-w+t		
Nenapregnuti štapovi	Ne	Ne	Ne	Neki dijag. ²
Maksimalna sila u nosećem kablu [kN]	365.980	602.013	885.619	156.937
Maksimalna sila u stabilizujućem kablu [kN]	314.678	368.648	859.882	273.576
Pomeranja u odnosu na projektovani položaj [m]	-0.2777	-0.2736	-0.1663	-0.2451

¹ Dijagonalni štap koji povezuje oslonac stabilizujućeg kabla i noseći kabl, i svi štapovi koji su „paralelni” s njim.

² Dijagonalni štap koji povezuje oslonac nosećeg kabla sa stabilizujućim kablom, i svi štapovi uz niži oslonac, koji su „paralelni” s njim.

Table 4. Parameters important for the stability of analyzed cable trusses

	Sports Hall in Bellingham (England)	Transitory Warehouse in Shiphall (the Netherlands)	The Ice Rink in Hall Johaneshov (Sweden)	Sports complex “Zdravlje” in Leskovac (Serbia)
Reference position	Prestress			
Designed position	Prestress and self weight			
(1) load phase		g		
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	512.328	860.247	1159.645	405.023
Maximum force in prestressing cable [kN]	276.156	338.104	852.455	210.725
Displacement from the reference position [m]	0.1877	0.3442	0.1874	0.1320
(2) load phase		g+s		
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	737.163	1118.094	1743.888	888.726
Maximum force in prestressing cable [kN]	183.646	242.893	651.260	122.844
Displacement from the reference position [m]	0.3514	0.3493	0.4542	0.2792

(3) load phase				
g+s-w				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	557.329	901.561	1507.784	581.215
Maximum force in prestressing cable [kN]	255.994	321.174	751.785	179.239
Displacement from the reference position [m]	0.0713	0.0523	0.2692	0.1038
(4) load phase				
g-w				
Non-stressed members	no	no	no	Some diag. ²
Maximum force in carrying cable [kN]	402.156	661.550	967.364	194.286
Maximum force in prestressing cable [kN]	335.104	398.773	911.259	296.851
Displacement from the reference position [m]	-0.0886	-0.2949	-0.1784	-0.2663
(5) load phase				
g-t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	540.863	880.818	1229.884	427.371
Maximum force in prestressing cable [kN]	297.095	353.324	949.431	230.347
Displacement from the reference position [m]	-0.0016	-0.0171	-0.0165	-0.0217
(6) load phase				
g+t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	484.796	809.471	1090.078	382.892
Maximum force in prestressing cable [kN]	254.204	299.668	814.646	191.480
Displacement from the reference position [m]	0.018	-0.0255	0.017	0.0237
(7) load phase				
g+s-t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	762.125	1136.690	1804.279	907.484
Maximum force in prestressing cable [kN]	206.402	258.162	729.567	142.829
Displacement from the reference position [m]	0.3308	0.3304	0.4293	0.2611
(8) load phase				
g+s+t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	712.537	1072.279	1684.366	870.296
Maximum force in prestressing cable [kN]	160.815	204.597	572.717	102.927
Displacement from the reference position [m]	0.3723	0.3791	0.4797	0.2973
(9) load phase				
g+s-w-t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	584.537	921.784	1571.237	601.161
Maximum force in prestressing cable [kN]	279.125	336.372	829.982	199.658
Displacement from the reference position [m]	-0.0531	0.040	0.2467	0.0861
(10) load phase				
g+s-w+t				
Non-stressed members	Some diag. ¹	Some diag. ¹	Some diag. ¹	Some diag. ¹
Maximum force in carrying cable [kN]	530.441	851.665	1445.192	561.676
Maximum force in prestressing cable [kN]	233.728	283.014	673.351	158.837
Displacement from the reference position [m]	-0.0899	0.0836	0.2922	0.1214
(11) load phase				
g-w-t				
Non-stressed members	no	no	no	Some diag. ²
Maximum force in carrying cable [kN]	439.825	685.507	1053.807	232.741
Maximum force in prestressing cable [kN]	355.455	411.798	983.680	320.191
Displacement from the reference position [m]	-0.3637	-0.3029	-0.1896	-0.2860
(12) load phase				
g-w+t				
Non-stressed members	no	no	no	Some diag. ²
Maximum force in carrying cable [kN]	365.980	602.013	885.619	156.937
Maximum force in prestressing cable [kN]	314.678	368.648	859.882	273.576
Displacement from the reference position [m]	-0.2777	-0.2736	-0.1663	-0.2451

¹ Diagonal member connecting the support of the prestressing cable and the carrying cable, and all members "parallel" to it

² Diagonal member connecting the support of the carrying cable and the prestressing cable, and all members "parallel" to it

5.1 Analiza rezultata

Proračun konstrukcija koje su prikazane, pokazuje da nisu ispunjeni svi uslovi stabilnosti koji se pominju u literaturi i primenjuju u praksi.

– **Sportska hala u Bilinghamu (Engleska)** zadovoljava u pogledu maksimalnih zatežućih sila u nosećem kablju, ali u minimalnoj meri ne zadovoljava u pogledu sila u stabilizujućem kablju (više za oko 1,5%), kao ni u pogledu pomeranja u odnosu na projektovani položaj konstrukcije (više za oko 7%). Takođe, pojasni noseći i stabilizujući kablovi jesu zategnuti u svim fazama opterećenja, a dijagonalni štapovi su zategnuti samo u fazi prednaprezanja, dok je u narednim fazama opterećenja svaki drugi štap nenapregnut.

– **Prolazni magacin u Šipholu (Holandija)** zadovoljava u pogledu maksimalnih zatežućih sila u nosećem i stabilizujućem kablju, ali je na granici zadovoljenja u pogledu pomeranja u odnosu na projektovani položaj konstrukcije. Takođe, pojasni noseći i stabilizujući kablovi su zategnuti u svim fazama opterećenja, a dijagonalni štapovi su zategnuti samo u fazi prednaprezanja, dok je u narednim fazama opterećenja svaki drugi štap nenapregnut.

5.1 The analysis of the results

The calculations of the constructions which are presented here show us that they have not satisfied all stability conditions which were mentioned in literature and used in practice.

– **Sports Hall in Bilingham (England)** Considering the maximum stressing forces in the carrying cable the construction is satisfactory, but it is minimally unsatisfactory concerning the forces in the stabilizing cable (1.5% greater), as well as concerning the movements in relation to the projected position of the construction which are 7% increased. Stripe cables: the carrying and stabilizing ones are stressed in all loading phases, the diagonal ones are stressed only in the prestressing phase, whereas in the following loading phases only each second one is prestressed.

– **Transitory Warehouse in Shiphall (the Netherlands)** Considering the maximum stressing forces in the carrying and stabilizing cable the construction is satisfactory, but it is hardly satisfactory considering the movements in comparison with the projected position of the construction. Stripe cables: the carrying and stabilizing ones are stressed in all loading phases, the diagonal ones are stressed only in the prestressing phase, whereas in the following loading phases only each second one is prestressed.

Tabela 5. Kriterijumi stabilnosti i sračunati parametri analiziranih kablovskih rešetaka

	Sportska hala u Bilinghemu, Engleska	Prolazni magacin u Šipholu, Holandija	Ledena dvorana u Johaneshovu, Švedska	Sportski kompleks „Zdravlje” u Leskovcu, Srbija
Nenapregnuti štapovi	Da – dijagon.	Da – dijagon.	Da – dijagon.	Da - dijag.
Maksimalna sila u nosećem kablju kN	762.125	1136.690	1804.279	907.484
Faza opterećenja	(7) g+s-t	(7) g+s-t	(7) g+s-t	(7) g+s-t
¹ Maks. dozvoljena sila u nosećem kablju kN (maksimalna sila multiplikovana odgovarajućim parcijalnim koeficijentom)	1463	2100	3969	1996
² Kataloška računsa prekidna sila	1570	2390	3650	2277
Maksimalna sila u stabilizujućem kablju kN	355.455	411.798	983.680	320.191
Faza opterećenja	(11) g-w-t	(11) g-w-t	(11) g-w-t	(11) g-w-t
⁽³⁾ Maks. dozvoljena sila u stabilizujućem kablju kN (maksimalna sila multiplikovana odgovarajućim parcijalnim koeficijentom)	711	824	2164	640
⁽⁴⁾ Kataloška računsa prekidna sila	700	933	2500	615
Maks.pomeranje u odnosu na projek. položaj m	-0.3637	-0.3791	-0.4797	0.2860
Faza opterećenja	(11) g-w-t	(8) g+s+t	(8) g+s+t	(11) g-w-t
³ Maks.dozv.pomer. u odnosu na projekt. polož. m	0.227	0.257	0.277	0.200
⁴ Maks.dozv.pomer. u odnosu na projekt. polož. m	0.340	0.385	0.415	0.300

Prema efektivnim kriterijumima projektnih jačina kablova.

² Prema katalogu proizvođača kablova.

³ Prema našem pravilniku za noseće čelične konstrukcije – ($L/300$).

⁴ Prema EC-3 maksimalni ugib za čelične konstrukcije – ($L/200$).

Table 5. Stability criteria and computed parameters of the analyzed cable trusses

	Sports Hall in Bellingham (England)	Transitory Warehouse in Shiphal (the Netherlands)	The Ice Rink Hall in Johaneshov (Sweden)	Sports complex "Zdravlje" in Leskovac (Serbia)
Non-stressed members	yes – diag.	yes – diag.	yes – diag.	yes – diag.
Maximum force in carrying cable kN	762.125	1136.690	1804.279	907.484
load phase	(7) g+s-t	(7) g+s-t	(7) g+s-t	(7) g+s-t
¹ Maximum allowed force in carrying cable kN (maximal force multiplied by partial coefficient)	1463	2100	3969	1996
² Catalogue calculation breaking force	1570	2390	3650	2277
Maximum force in prestressing cable kN	355.455	411.798	983.680	320.191
load phase	(11) g-w-t	(11) g-w-t	(11) g-w-t	(11) g-w-t
⁽³⁾ Maximum allowed force in prestressing cable kN (maximal force multiplied by partial coefficient)	711	824	2164	640
⁽⁴⁾ Catalogue calculation breaking force	700	933	2500	615
Maximum displacement from the designed position m	-0.3637	-0.3791	-0.4797	0.2860
load phase	(11) g-w-t	(8) g+s+t	(8) g+s+t	(11) g-w-t
³ Maximum allowed displacement from the designed position m	0.227	0.257	0.277	0.200
⁴ Maximum allowed displacement from the designed position m	0.340	0.385	0.415	0.300

¹ According to effective criteria of design strength of cables

² According to the catalogue of the cable manufacturer

³ According to our regulations for steel structures – ($L/300$)

⁴ According to EC-3 maximal deflection for steel structures – ($L/200$)

– **Ledena dvorana u Johaneshovu (Švedska)** ne zadovoljava u pogledu maksimalnih zatežućih sila u nosećem kablju ($2,2 \cdot 1804,3 = 3969 \text{ kN}$, što je za oko 9% više od sile kidanja 3650 kN), ali zadovoljava u pogledu sila u stabilizujućem kablju. Ne zadovoljava ni u pogledu pomeranja u odnosu na projektovani položaj konstrukcije (sračunato maksimalno pomeranje je $0,48 \text{ m}$, a minimalni kriterijum pomeranja $L/200 = 0,415 \text{ m}$, što je za oko 16% više). Takođe, pojasni noseći i stabilizujući kablovi jesu zategnuti u svim fazama opterećenja, a dijagonalni štapovi su zategnuti samo u fazi prednaprezanja, dok je u narednim fazama opterećenja svaki drugi štap nenapregnut.

– **Sportski kompleks „Zdravlje” u Leskovcu (Srbija)** zadovoljava u pogledu maksimalnih zatežućih sila u nosećem kablju, dok u pogledu sila u stabilizujućem kablju, prekoračuje granicu iskorišćenosti za oko 4%. Pomeranja u odnosu na projektovani položaj konstrukcije $0,286 \text{ m}$ zadovoljava po EC-3, dok po našim propisima za metalne konstrukcije $L/300 = 0,200 \text{ m}$ (veći je od dozvoljenog za oko 43%). Pojasni noseći i stabilizujući kablovi jesu zategnuti u svim fazama opterećenja, a dijagonalni štapovi su zategnuti samo u fazi prednaprezanja, dok je u narednim fazama opterećenja svaki drugi štap nenapregnut.

Poređenjem veličine pomeranja čvorova dobijenih

– **The Ice Rink Hall in Johaneshov (Sweden)**

Considering the maximum stressing forces in the carrying cable the construction is unsatisfactory ($2,2 \cdot 1804,3 = 3969 \text{ kN}$ which is approximately 9% greater than the tearing force 3650 kN ; yet it is satisfactory considering the forces in the stabilizing cable. It is unsatisfactory considering the movements in relation to the projected position of the construction (the maximum calculated movement was $0,48 \text{ m}$, and the minimum criterion of displacement $L/200 = 0,415 \text{ m}$, which is approximately 16% greater). Stripe cables: the carrying and stabilizing ones are stressed in all loading phases, but the diagonal rods are stressed only in the prestressing phase, whereas in the following loading phases each second rod is unstressed.

– **Sport Complex “Zdravlje” in Leskovac (Serbia)**

Considering the maximum stressing forces in the carrying cable the construction is satisfactory, yet considering the forces in the stabilizing cable it is above the use limitations for approximately 4%. The movements in relation to the projected position of the construction of $0,286 \text{ m}$ are satisfactory according to EC-3, whereas according to our regulations for metal constructions $L/300 = 0,200 \text{ m}$ they are larger than allowed, for approximately 43%. Stripe cables: the carrying and the stabilizing one are stressed in all of the

primenom kombinovane analitičko-numeričke metode (Tabela 5) sa originalnim dostupnim rezultatima (Tabela 1), uočavaju se bitne razlike date u Tabeli 6.

loading phases, the diagonal rods are stressed only in the prestressing phase; whereas in the following loading phases each second rod is unstressed.

Comparing the results of movements values obtained using the combined analytical-numerical method (Table 5) with the original available results (Table 1) some very important differences were noticed. They are given in Table 6.

Tabela 6. Odstupanja sračunatih maksimalnih originalnih pomeranja i rezultata dobijenih programom „Cabl” analiziranih kablovskih rešetaka, izraženo u m

Table 6. Deviation of calculated maximal original displacements from the results obtained by the program “Cabl” of the analyzed cable trusses, in m

	Sportska hala u Bilinghemu, Engleska Sports Hall in Bellingham (England)	Prolazni magacin u Šipholu, Holandija Transitory Warehouse in Shiphall (the Netherlands)	Ledena dvorana u Johaneshovu, Švedska The Ice Rink Hall in Johaneshov (Sweden)	Sportski kompleks „Zdravlje” u Leskovcu, Srbija Sports complex “Zdravlje” in Leskovac (Serbia)
(2) faza opterećenja / load phase				
g+s				
Originalni rezultat-analitički metod ¹ Original result-analytical method ¹	0,530	0,400	0,430	0,204
Analitičko-numerički metod (program „Cabl”) Analytical-numerical method (program “Cabl”)	0,351	0,349	0,454	0,279
Korekcija / Correction	0,179	0,051	0,024	0,075
Odstupanje / Deviation	50%	14,6%	5,3%	26,9%
(2) faza opterećenja / load phase				
g-w				
Originalni rezultat-analitički metod ¹ Original result-analytical method ¹	-0,280	-0,310	-0,180	-0,142
Analitičko-numerički metod (program „Cabl”) Analytical-numerical method (program “Cabl”)	-0,089	-0,295	-0,178	-0,266
Korekcija / Correction	0,191	0,015	0,002	0,124
Odstupanje / Deviation	215%	5,1%	1,1%	46,6%

Osim za Sportski kompleks „Zdravlje”, gde je primenjen Transient Stiffness Method

¹ Except for the Sports complex “Zdravlje” where Transient Stiffness Method is applied

Velika odstupanja u odnosu na analitičku metodu moguća su zbog aproksimacija koje se uvode prilikom rešavanja analitičkih jednačina, kao i mogućih grešaka u rasporedu štapova ispune (formiran model ne odgovara stvarnoj konfiguraciji štapova ispune nosača). Kod objekata u Holandiji i Švedskoj odstupanja su zanemarljiva. Veća odstupanja kod objekata u Engleskoj i Srbiji mogu da se pripišu neverodostojnom i nelogičnom podatku iz literature (Tabela 1, [14, 10]).

Primena kombinovane analitičko-numeričke metode ukazala je na to da se brže i jednostavnije dolazi do rezultata proračuna kablovskih rešetaka primenom programa „Cabl”. Ne pojavljuju se singularna matrica i prekid proračuna, jer su početni parametri koji se koriste u prvoj iteraciji Transient Stiffness Method dovoljno tačni da se proračun uvede u dalji iterativni postupak. Korišćenjem analitičkog metoda prof.Balgača, kontrola sile prethodnog naprezanja svedena je na ekvivalent dodatnog gravitacionog opterećenja, što umnogome pojednostavljuje analizu ovih nosača.

If compared with the analytical method, greater deviations are possible because of the approximations which were introduced while solving the analytical equations, as well as because of the possible errors in the distribution of filling rods (the model which was formed does not correspond to the real configuration of the girder’s nodes and members configuration). The deviations are insignificant in the structures in the Netherlands and Sweden. Greater deviations in the constructions in England and Serbia might be caused by the inauthentic and illogical data from literature (Table1, [14, 10]).

The use of the combined analytical-numerical method proved that it is much easier to obtain calculation results of cable trusses applying programme “Cabl”. There are no singular matrices and calculation interruptions since the initial parameters used in the first iteration of the Transient Stiffness Method are enough accurate so that the calculation can be proceeded into the following iterative procedure. Using the analytical method of professor Balgac, the control of the

6 ZAVRŠNE NAPOMENE, ZAKLJUČCI I PREPORUKE

Analizom nekoliko karakterističnih konstrukcija kablovskih rešetaka, došlo se do određenih zaključaka:

- opravdana je upotreba analitičko-numeričkog metoda za analizu ovog tipa konstrukcija (korekcije sila i pomeranja analitički dobijenih parametara vrlo su male [1, 12, 13]).

- Transient stiffness metodom preračunate su sile i pomeranja za dvanaest slučajeva statičkog opterećenja i izvedeno je poređenje s važećim kriterijumima stabilnosti. Utvrđeno je da se u skoro sva četiri analizirana slučaja konstrukcija javljaju u manjoj ili većoj meri prekoračenja maksimalne sile u nosećem ili stabilizujućem kablju, nenapregnuti štapovi dijagonala u nekim od slučajeva opterećenja, kao i pomeranja veća od dozvoljenih.

- Nenapregnutost štapova ispune u pojedinim fazama opterećenja dovodi do veće horizontalne pomerljivosti i mogućeg vitoperenja nosača u vertikalnoj ravni. Vitoperenje nosača može da dovede do veće horizontalne pomerljivosti i stvaranje uslova za rezonantne efekte. Krovni nosači uglavnom ispunjavaju kriterijume statičke stabilnosti, ali se iz aspekta postizanja dinamičke stabilnosti postavlja pitanje dovoljne sile prednaprezanja kako bi se zadovoljili kriterijumi 2.e [3, 11-14].

S obzirom na duži period eksploatacije ovih objekata i osavremenjene kriterijume stabilnosti, a imajući u vidu prezentirane rezultate, nameće se potreba procene stabilnosti i bezbednosti korišćenja ovih objekata. Preporuke autora ovog rada jesu:

- Makroskopski detaljni pregled kablovskih struktura u pogledu mehaničkih i hemijskih oštećenja nosećih i spojnih elemenata;

- Precizno utvrđivanje trenutne geometrije nosača pod stalnim opterećenjem geodetskim metodama;

- Realni statički i dinamički uticaji (opterećenja) koji deluju na krovnu površinu;

- Ispitivanjem utvrditi deformacije usled probnog opterećenja i svojstvene vibracije kablovskih nosača;

- Sprovesti ponovnu statičku analizu za utvrđene realne uticaje na osnovu geodetskog snimka konfiguracije nosača i karakteristika kablova;

- Izvršiti dinamičku analizu uticaja vetra za lokalne uslove i mogućnost pojave rezonance [1];

- Izvesti konačan zaključak u pogledu ispunjenja kriterijuma stabilnosti a-e iz odeljka 2 ovog rada.

prestressing forces is reduced to the equivalent of the additional gravity loading, which makes the analysis of the girders much more simple.

6 FINAL REMARKS, CONCLUSIONS AND RECOMMENDATIONS

Having analyzed several characteristic constructions consisting of cable trusses some specific conclusions were made:

- The use of analytical-numerical method for analyzing this type of constructions is justified. (Movements and forces corrections of analytically obtained parameters are very small) [1, 12, 13]

- Using the Transient Stiffness Method the forces and displacements in 12 cases of static loadings were calculated and compared to the already updated stability criteria. It was determined that in all of the four analyzed structures there were some exceed of the maximum forces either in the carrying or in the stabilizing cable, that there were some unstressed diagonal rods in some loading cases, and that there were some movements greater than the allowed ones.

- The unstressed filling rods in some loading cases cause greater horizontal movability and possible bending of a girder in the vertical plane. The bending of a girder can cause a larger horizontal movability and make conditions for resonance effects. Roof girders satisfy the criteria in most of the cases. However, concerning the aspects of reaching dynamic stability there is a problem of the sufficient prestressing force so that the criteria could be fulfilled.

Bearing in mind that the buildings have been used for quite long period of time, that stability criteria were updated and all the results were presented in the paper, it is necessary to estimate their stability properly as well as their safe use. The authors' recommendations are:

- Macroscopic detailed examination of cable structures concerning mechanic and chemical damages in the carrying and connecting elements,

- Precise estimation of girders' geometry under constant loading using geodetic methods

- Estimating real static and dynamic influences (loadings) which affect the roof surface,

- Measuring deformations caused by experimental loading and own vibrations of cable girders,

- Making repeated static analysis for estimation of real influences based on the geodetic estimation of girders' and characteristic cables' configuration,

- Making dynamic analysis of the influence of wind gusts for the local position and possible occurrence of resonance [1],

- Drawing final conclusion on the fulfillment of updated stability criteria (a-e from Chapter 2 of the Paper).

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REZIME

ANALIZA STABILNOSTI NEKIH IZVEDENIH KABLOVSKIH REŠETAKA

*Dragan KOSTIĆ
Vuk MILOŠEVIĆ*

U ovom radu prikazani su i analizirani primeri izgrađenih kablovskih rešetaka za pokrivanje velikih raspona, prema odabranim dostupnim podacima iz literature. Globalni odgovor konstrukcije na statička opterećenja, korišćenjem originalnog softvera kombinovanom analitičko-numeričkom metodom, pruža mogućnost dublje analize odabranih sistema. Tako dobijeni rezultati analizirani su iz aspekta kriterijuma stabilnosti, u odnosu na statička opterećenja (minimalne sile prednaprezanja, pojava nenapregnutih štapova, maksimalna pomeranja). Poređenjem dobijenih podataka s važećim kriterijumima stabilnosti, komentariše se trenutno stanje i formuliše se predlog za poboljšanje stabilnosti analiziranih kablovskih rešetaka.

Ključne reči: stabilnost, kablovske rešetke, transient stiffness metoda, force density metoda, dozvoljena pomeranja

SUMMARY

ANALIZA STABILNOSTI NEKIH IZVEDENIH KABLOVSKIH REŠETAKA

*Dragan KOSTIC
Vuk MILOSEVIC*

This paper is both a presentation and an analysis of some built cable trusses used for covering large spans according to some data which were selected and available from the literature. An overall response of a construction to static loadings applying the original software of the combined analytical-numerical method gives the possibility of a more comprehensive analysis of the chosen systems. The results obtained in this way were analyzed concerning stability criteria in relation to static loadings (minimum forces of prestressing, the occurrence of unstressed rods, exceeded displacement). Having compared the obtained data with the updated stability criteria we comment the present situation and suggest the ways of improving the stability of the cable trusses which were analyzed.

Key words: stability, cable trusses, transient stiffness method, force density method, allowed displacements