FORM FINDING AND STRUCTURAL ANALYSIS OF CABLES WITH MULTIPLE SUPPORTS

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CABLES WITH MULTIPLE SUPPORTS

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ABSTRACT

FORM FINDING AND STRUCTURAL ANALYSIS OF

CABLES WITH MULTIPLE SUPPORTS

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Cables are highly nonlinear structural members under transverse loading. This nonlinearity is mainly due to the close relationship between the final geometry under transverse loads and the resulting stresses in its equilibrium state rather than the material properties. In practice, the cables are usually used as isolated single-segment elements fixed at the ends. Various studies and solution procedures suggested by researchers are available in the literature for such isolated cables. However, not much work is available for continuous cables with multiple supports.

In this study, a multi-segment continuous cable is defined as a cable fixed at the ends and supported by a number of stationary roller supports in between. Total cable length is assumed constant and the intermediate supports are assumed to be frictionless. Therefore, the critical issue is to find the distribution of the cable length among its segments in the final equilibrium state. Since the solution of single-segment cables is available the additional condition to be satisfied for multi-segment continuous cables with multiple supports is to have stress continuity at intermediate support locations where successive cable segments meet. A predictive/corrective iteration procedure is proposed for this purpose. The solution starts with an initially assumed distribution of total cable length among the segments and each segment is analyzed as an independent isolated single-segment cable. In general, the stress

continuity between the cable segments will not be satisfied unless the assumed distribution of cable length is the correct distribution corresponding to final equilibrium state. In the subsequent iterations the segment lengths are readjusted to eliminate the unbalanced tensions at segment junctions. The iterations are continued until the stress continuity is satisfied at all junctions. Two alternative approaches are proposed for the segment length adjustments: Direct stiffness method and tension distribution method. Both techniques have been implemented in a software program for the analysis of multi-segment continuous cables and some sample problems are analyzed for verification. The results are satisfactory and compares well with those obtained by the commercial finite element program ANSYS.

Keywords: Single-segment cable, multi-segment continuous cable, continuous cable with multiple supports, tension distribution for continuous cables, Newton-Raphson iterations

ÖZ

ÇOK MESNETLİ KABLOLARIN

YAPISAL ANALİZİ VE ŞEKİL TAYİNİ

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Yüksek Lisans, İnşaat Mühendisliği Bölümü

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Kablolar yanal yük altındaki davranışı yüksek derecede doğrusal olmayan yapı elemanlarıdır. Bu durum kabloların malzeme özelliklerinden çok uygulanan yükler altındaki denge koşulları ile son denge konumundaki geometrisi arasındaki direkt ilişkiden kaynaklanmaktadır. Uygulamada kablolar genellikle uç noktalarından sabitlenmiş tek bir eleman olarak kullanılmakta ve bu şekilde analiz edilmektedir. Literatürde böyle iki ucundan mesnetli tek parça kabloların analizi için birçok çalışma ve çözüm önerileri mevcuttur. Ancak çok mesnetli sürekli kablolar için fazlaca bir çalışma bulunmamaktadır.

Bu çalışmada her iki ucundan mesnetlenmiş ve bu mesnetler arasına yerleştirilmiş sabit makaralı mesnetler ile desteklenmiş çok açıklıklı ve çok mesnetli sürekli kabloların analizi için bir çözüm yöntemi geliştirilmiştir. Kablo sisteminin toplam boyunun sabit, ara mesnetlerin ise sürtünmesiz makaralar şeklinde olduğu kabul edilmektedir. Uç noktalarından mesnetlenmiş ve sabit boydaki kablolar için çözüm yöntemi bilindiğinden sürekli kablolar için çözülmesi gereken problem, sistemin son denge konumunda, toplam kablo boyunun açıklıklar arasındaki dağılımının belirlenmesidir. Bunun için sürekli kablo sisteminde tek açıklıklı izole kablo çözümüne ilave olarak sağlanması gereken temel koşul ara mesnet noktalarındaki kablo gerilmelerinin sürekliliğidir. Önerilen iteratif çözüm yönteminde analize kablo

toplam boyunun açıklıklar arasına makul bir dağılımı ile başlanmakta ve herbir açıklıktaki kablo izole tekil bir kablo olarak çözülmektedir. Daha sonra kablo boyunun açıklıklar arasındaki dağılımı ara mesnet noktalarında ardaşık kablo bölümleri arasında oluşan gerilme farkını sıfırlayacak şekilde yeniden belirlenmekte ve iterasyonlara sistem denge konumuna ulaşana kadar devam edilmektedir. Bu amaçla iki farklı yaklaşım önerilmektedir: Direkt rijitlik yöntemi ve gerilme dağıtma yöntemi. Çok mesnetli sürekli kabloların analiz amacı ile her iki yöntemi de kullanan bir yazılım geliştirilmiş ve değişik yapıdaki örnek kablo sistemler çözümlenmiştir. Elde edilen sonuçlar tatmin edici olup ticari bir sonlu elemanlar yazılımı olan ANSYS programı ile elde edilen sonuçlar ile uyum içinde olduğu görülmektedir.

Anahtar Kelimeler: Tek açıklıklı kablo, çok açıklıklı sürekli kablo, çok mesnetli sürekli kablo, sürekli kablolar için gerilme dağıtma yöntemi, Newton-Raphson iterasyonu

To My Family

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Thanks to my family DEMİR; KERİM, AYŞE, ÖZLEM, HAVVA NUR

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

L_U	: Unstressed length of cable
L_S	: Stressed length of cable
$\vec{P}_A$	: Position vector of point A
$\vec{P}_B$	: Position vector of point B
l_u	: Unstressed arc length form point A to M
l_s	: Stressed arc length from point A to M
$\hat{\tau}(l_u)$	: Unit tangent at point M
$\vec{R}(l_u)$	: Reaction vector at point M
$T(l_u)$	: Reaction at point M
Δl_u	: Elongation of the element at point M
$\varepsilon(l_u)$	: Strain of the element at point M
$[S]$	: Stiffness matrix
$\vec{F}_{ext}(l_u)$	: Total force applied to cable form point A to M
$\vec{W}$	: Distributed load on cable including self weight
E	: Modulus of elasticity of cable material
A	: Cross-sectional area of cable
υ	: Cable constitutive constant
$\hat{i}$, $\hat{j}$, $\hat{k}$	: Unit vectors along global coordinate directions X, Y, Z respectively

$[F]$	: Flexibility matrix
$\vec{M}^{[i]}$	: Misclose vector
ERR	: Target error or precision
$E^{[i]}$	: Error at ith iteration
$l_{u(i)}$, $l_{s(i)}$	: Unstressed and stressed length of cable on ith segment
$\Delta\vec{R}_{(i)}$	: Reaction difference of cable on ith roller support
$\vec{R}_{F(i)}$	: Reaction vector for the first node of the ith segment
$\vec{R}_{L(i)}$	: Reaction vector for the last node of the ith segment
$\Delta T_{(i)}$	: Tension difference of cable on ith roller support
$\Delta L_{U(i)}^{segment}$	: Length adjustment applied on ith segment
$\Delta L_{U(i)}$	: Length adjustment applied on ith roller support
$\delta T_{(i)}$	: Change in unbalanced tension on ith roller support
$\delta L_{U(j)}$	: Unstressed length adjustment on jth roller support
$[K]$	: Stiffness matrix of multi segment continuous cable
f	: Flexibility coefficient
$l_{u(i)}^{[m]}$	: Unstressed length of cable on ith segment for mth iteration

CHAPTER 1

INTRODUCTION

1.1 General

Cables, having negligible shear, flexural and torsional rigidities and zero-buckling load, are invaluable members for structural engineering. They are used in many structures like guyed towers, cable-stayed bridges, marine vehicles, offshore structures, cable roofs, transmission lines, pre-stressing applications and tensegrity works. Mostly, cables are used for large span distances and/or pre-stressing works.

Nonlinearity is a problem for almost all structural elements. In basic, these nonlinearities occur due to geometrical and material properties of the member. Both of them are valid for almost all structures. If the member is adequately stiff in lateral direction, the geometrical nonlinearity could be ignored due to small P-Δ effect. However, cable is a structural element which has a very small stiffness in lateral direction because of its tangential geometry. Steel is used as a material for fabrication of cable. Therefore, cable has the nonlinearity of steel material. Besides, tangential geometry of the cable gives the cable element another nonlinearity due to squeeze which could not be classified as purely geometrical or material nonlinearity. Thus, cable is a nonlinear structural element due to its geometry and material properties. In this study, modulus of elasticity of the cable material is taken constant. Only geometric nonlinearity is taken into account.

In structures, both in designing stage and application stage, cables are used as supported between the two end points. According to this design, cables have a fixed unstretched length between those supports. The lengthening is only due to stresses applied on it. However, if cables are designed monolithically and supported by a number of roller supports, there will be a change in unstretched length of cable for each segment due to loads applied on it. This behavior of cable adds another nonlinearity to the problem.

In practice, cables are designed as a single-segment and assumed to be linear structural members. For example, a type of pre-stressing work, shown in Figure 1.1, is a completely single-segment multi-support cable problem. A monolithic tendon placed between two end points and supported by a number of roller supports along its span is a truly nonlinear problem. However, the cable is usually assumed as a linear member to ease the calculations for this pre-stressing work. Although, the weight of the cable is negligible for small-scale problems like this example, the cable cannot be classified as a linear structural member for large scale problems.

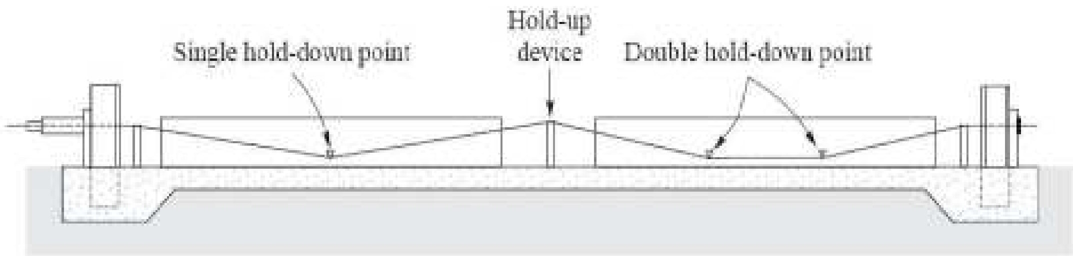

Figure 1.1 Pre-stressing by draping the tendons.

In brief, depending on the way they are used in structures, the cable behavior under transverse loading is a nonlinear problem. In many situations, they are supported not only at their end points but also at some points along their spans. This, in turn, further increases the level of nonlinearity due to presence of contact problem. However, in practice, they are usually treated as single-segment systems and assumed as linear structural members supported at their end points. This research gives a different point of view to the analysis of cables supported along their spans.

1.2 Purpose

Extensive research has been made under the constraint that loads are applied to some predefined points on the cable or successive cables are designed separately. This design logic restricts engineers to design more integrated systems. Because there could be a number of cable elements in a structure and these cables are designed as single-segment. All cable elements should be designed and lengths of them should be determined individually. Besides that restriction of engineer aspect, there are many structures designed as single-segment cable systems although being multi-segment continuous cable systems. As an example, draglifts are systems having multi-segments cable. Instead of the constraint of single-segment cable systems, research was made to see the behavior of cables placed on roller supports. This approach will give engineers a wide aspect for designs and research. Also it makes convenient designs possible. Previous studies and objective study are illustrated in Figure 1.2 and Figure 1.3, respectively.

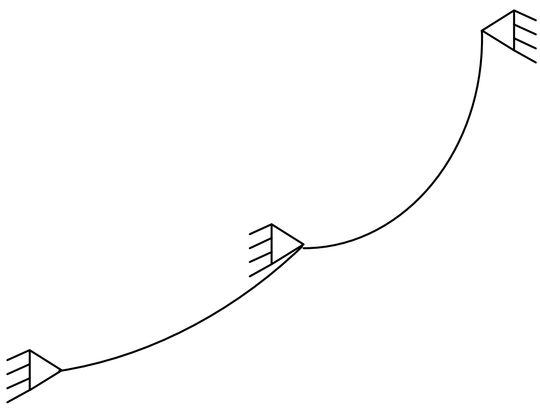

Figure 1.2 Single-segment cable profile.

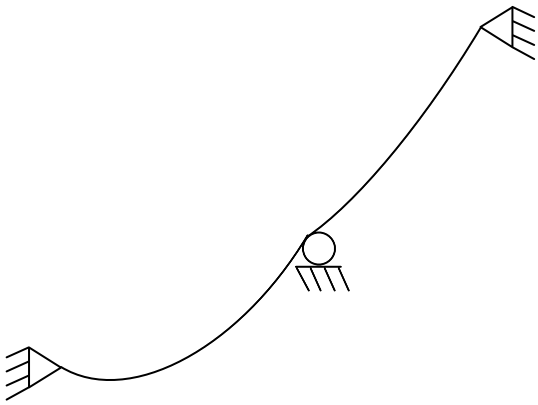

Figure 1.3 Multi-segment continuous cable profile.

1.3 Previous Studies

Being a useful member for structural systems, make cables more attractive for researchers. Despite being an important material, it is hard to analyze the cables because cables are highly nonlinear structural components. These nonlinearities are due to its material characteristic and behavior under applied loads. Although these are denoted in different ways, they could not be distinguished. Also, this association makes the problem more complex. Besides, having many types make cable analysis harder. Convoluted geometry and some types of cables are shown in Figure 1.4 and Figure 1.5. These complicated characteristics of cables have been studies of researchers for a half century. Studies, which have been carried out previously, are processed into that order; material characteristics of cable, equivalent modulus approach, finite element approach, single-segment and multi-segment studies.

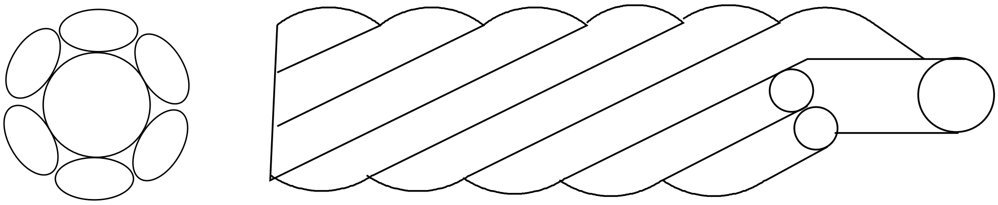

Figure 1.4 Cross-section and layout of 7 wire strands

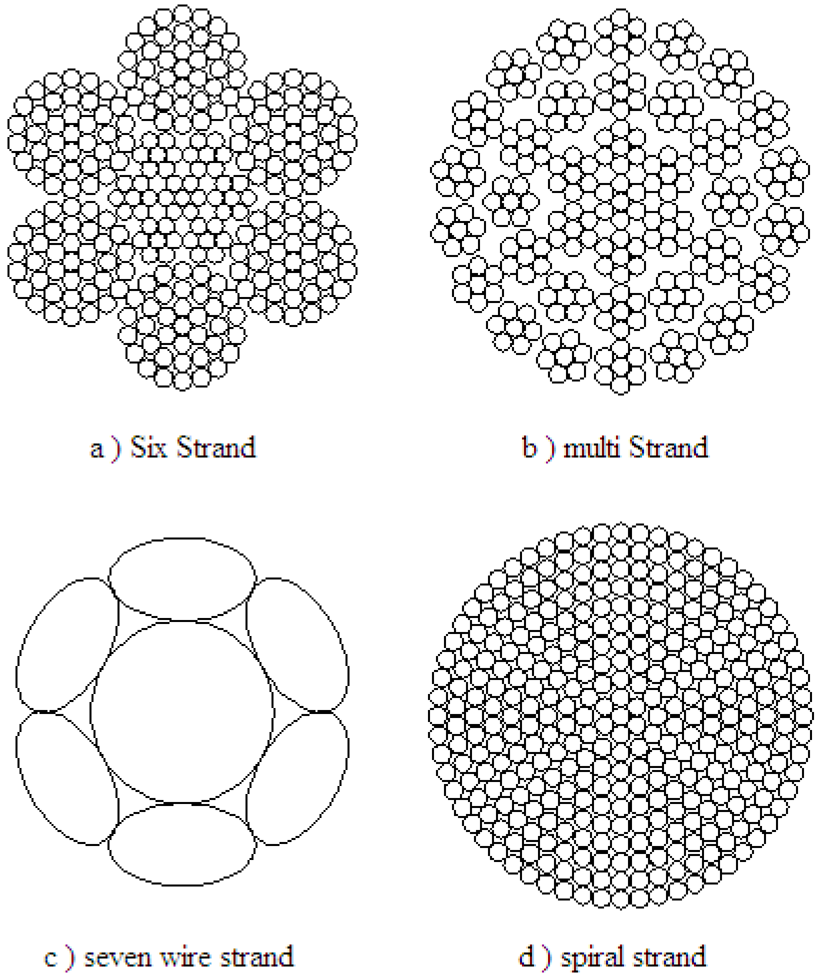

Figure 1.5 Some types of strands

Stress - strain relationship of cables are hard to determine. Its response under some stresses shows discrepancy between under low stresses and high stresses. Cables show relaxation under stresses due to its tangential geometry. If a strain controlled test is made for cables, it will be seen that relationship with stress is not linear and the stress - strain graph shows typical inclinations for different types of cables. These inclinations are illustrated in Figure 1.6. Analyses on stress-strain relationship of cables were made by several authors. The earlier study was made by Costello [1], then by Kumar and Cochran [2]. They tried some theoretical approaches related with cables' tangential geometry and found some formulas modeling the behavior of cables. These formulas were compared with stress – strain analysis and accuracy of them were determined.

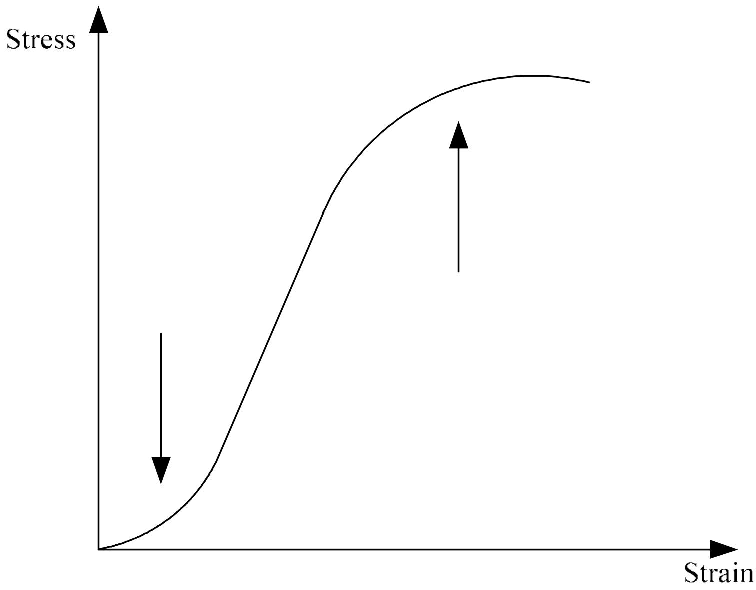

Figure 1.6 Typical stress-strain relationship of cable

Behavior under applied loads and self weight is another nonlinearity of cable analysis. Although there were studies made before 1950s, there was no tangible research for cables and their nonlinear behavior. They assumed linear behavior for cable. Some researchers tried to make cable analysis after 1950s, nevertheless studies had not been solved the nonlinear behavior of cables, precisely, until 1980s.

Between 1950s and 1980s, researchers only made some assumptions to minimize the nonlinear behavior. Researchers performed catenary cable analysis by some approaches. Equivalent modulus of elasticity is an approach for reaching the catenary behavior of the cables before computers. This approach was first discussed by F. Dischinger [3]. Positioning the catenary cable's shape as parabola instead of its real shape and neglecting the cable weight are assumptions made in equivalent modulus of elasticity approach. Equivalent secant modulus of elasticity is another approach, formulated by Ernst [4]. Hajdin et al. [5] redefined the cables' equivalent modulus in 1998.

Dischinger's formula [3];

$$\overline{E}A = \frac{EA}{1+\frac{1}{12}\left(\frac{g_z l}{T^2}\right)^2 EAT} \tag{1.1}$$

Hajdin, Michaltsos and Konstantakopoulos [5] derivation result;

$$\overline{E}A = \frac{EA}{1+\frac{EA\left(g_z l\right)^2}{24}\frac{\left(\overline{T}+T-\frac{2}{3}g_x l\right)}{\left[T\overline{T}-\frac{g_x l}{3}\left(T+\overline{T}\right)+\left(\frac{g_x l}{3}\right)^2\right]^2}} \tag{1.2}$$

Computer, being a milestone for structural engineering in 1980s, makes some calculations possible, easy and accurate. This is valid for cable analysis. Computer makes nonlinear analysis easy and possible. Finite element modeling was used for nonlinear analysis after the invention of computer.

Finite element method is a model, originally introduced by Turner et al. [6]. FEA is a numerical technique for approximate solutions of complex problems. These complexities were called as "real world" problems by Madenci et al. [7]. Some material, shape and boundary condition properties of problem cause complexities. All complexities or nonlinearities are valid for cable problem.

The basis of FEA is decomposition of system to find out the solution of the total system. Each decomposed member of system is called as finite element. Although Turner et al. [6] established the element matrix assembly; the "finite element" term was first used by Clough [8]. Idea of FEA does not change; nevertheless there are lots of finite element types and solution types for problems. The solution will be approximate, changing with solution techniques e.g. finite element length and shape function. However, the finite element solutions will approach to the correct result with the mesh refinement.

The first realistic single-segment cable solution was made by Michalos and Brinstiel [9]. Skop and O'Hara [10,11] made similar analysis. Approach of this study is a finite element analysis having trial and error procedure. Procedure of the study is:

Cable having supports at both ends is an indeterminate structure, so system is assumed as one end supported cable to make system statically determinate. Then, cable layout is formed by finite element analysis procedures. First support's reactions are changed by some iterative procedures till cable's other cusp ends on second support.

The iterative procedure used by Skop and O'Hara [10,11] is called Method of Imaginary Reactions. Some research were made on this iterative procedure technique. Newton Raphson Method was introduced by Polat M.U. in his master thesis [12] by the supervision of Yılmaz Ç.. Method of Imaginary Reactions and Newton Raphson Method has same technique in positioning of cable, they differ in iteration phase. Newton Raphson Method is used in this thesis to decreases the number of iterations.

Various computer programs have been developed for analysis of cable till now. Peyrot and Goulois developed one of them [13]. Also, Fleming J.F. [14] coded a program for nonlinear static analysis of cable-stayed bridge structures which includes cable analysis. Almost all of them were written by finite element modeling. Also, CABPOS is finite element modeling computer program for cable analysis developed within this theses. Except that affinity, CABPOS solves multi-segment continuous cable systems, while others deal with single-segment cable solutions.

Multi-segment continuous cables are used in daily life. Cable lift, Barriers for highways, ski tows and teleskis are systems work with cables having multi-segments. These systems were analyzed by the logic of single-segment cable analysis. Charland J.W. et all deal with multi-segment continuous cable problems [15] by breaking cable into segments. They dealed with wood logging systems as seen in Figure 1.7. There are two supports and a roller support. Charland J.W. called end supports as Skyline anchor point and roller support as Intermediate support. They coped with this cable problem by some assumptions. These assumptions are;

1- Cables are assumed to be massless and inextensible.
2- Friction is ignored in the formulation.
3- Tension in each cable is considered to be constant along the cable.

4- Intermediate support is a support which does not make any interaction between two successive supports.
5- Length of cable at segments does not change.

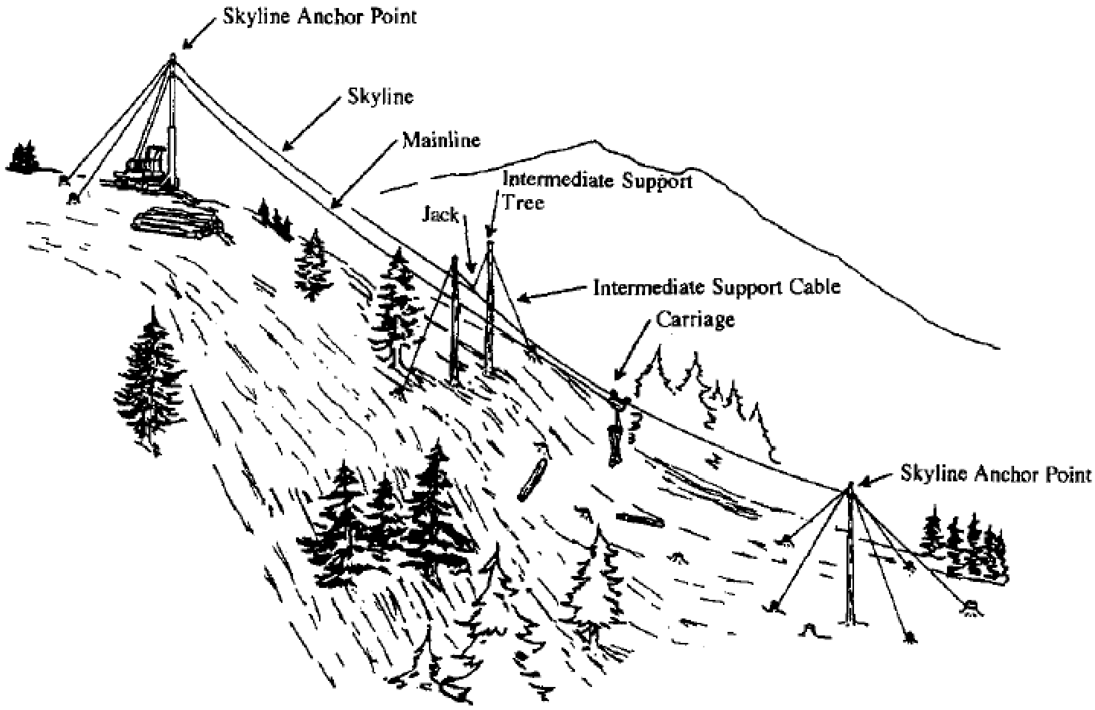

Figure 1.7 Illustration of cable logging system by Charland J.W.[15]

Briefly, Charland J.W. [15] defined a multi-segment continuous cable problem in 1994; however solution of the system is not achieved correctly. The assumptions made by Charland J.W. simplify the system and made it single-segment cable.

Aufaure M. [16] also defines a multi-segment continuous cable problem. Researcher dealed with an electricity cable problem having three supports. In this study, a cable element having three nodes N1, N2, N3 is defined. N1 and N2 are fixed nodes. N3 is the node which coincides with roller support. This coincidence is found by the continuity of the tension in the cable. Aufaure M. also made some assumptions. The most important assumption is: Node N3 must remain between N2 and N1. If not, convergence does not been reached and new length for an element must be selected. So, this solution depends on cable element length. Therefore, longer elements will be needed for slack cable problems. Another handicap of the solution is that; this solution technique is valid for two segment cable systems.

Kwang Sup Chung et all [17] studied on a cable-stayed bridge which has multi-segment continuous cable system. In their study, they worked on a bridge having cable with a roller support. This bridge is a cable-stayed bridge having saddle anchorage, which can be called roller support, in Austria. They used finite element model for the solution of cable system. They consider the sliding effect on roller support. Two type of sliding effect is defined by the authors. These are roller sliding without friction and frictional sliding. Finally, they define a new problem faced on cable-stayed bridges and solve it. This problem is a nonlinearity of usage of multi-segment continuous cables on structures. However this solution was also a single-segment cable solution. They did not deal with the interchange of the cable on the roller support. Their solution is for friction problem.

The photos of that bridge taken by the author of that study are shown in Figure 1.8 and Figure 1.9. This type of roller supports could be seen on lots of structures mostly in bridges. For instance, pylons of suspension bridges commonly consist a roller support. However the effect of roller support does not considered also for those examples.

Figure 1.8 Whole view of the bridge [17]

Figure 1.9 View of the saddle [17]

Kyoung-Bong H. and Sun-Kyun P. [18] defined another multi-segment continuous cable system. They tried to increase the load-carrying capacity of truss system. They applied a multi-segment continuous cable system to truss system with the logic of post-tensioning. A monolithic cable was used for those systems, because it was applied to an existing structural system. Thus, post-tensioning should be applied by one jacking operation. They made a parametric study on this system. Many types of cable configurations were given in the study. One example of those is in Figure 1.10. However, cable is assumed as a linear element and interchange on roller supports is not considered.

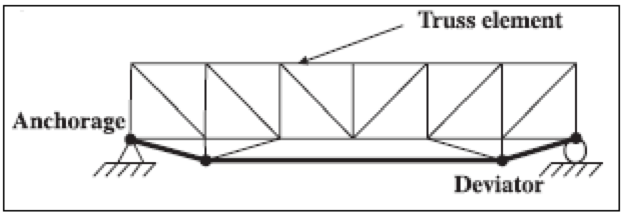

Figure 1.10 Post-tensioned truss bridge [18]

Cable has two segments and/or the structural system is symmetric or cable is assumed as linear element in almost all structural systems mentioned above. Although there are various types of solutions and techniques for cable analysis, these could only give a solution for single-segment cable or partially for multi-segment continuous cable.

CHAPTER 2

SINGLE-SEGMENT CABLE

2.1 General

Cables are highly nonlinear in their response under applied transverse loading. The nonlinearity is mainly due to interaction between its deformed geometry and the resulting stresses in its final equilibrium state. Early researchers have tried to analyse cables by adjusting the mechanical properties after some simplifying assumptions and completely ignoring the geometric component of nonlinearity. However, the resulting Equivalent Modulus Approach was, naturally, far from yielding satisfactory results. Correct solutions were obtained by the Method of Imaginary Reactions [10] and nonlinear finite element analysis using Newton-Raphson iterations. These analysis techniques are the extension of the Theory of Consistent Deformations. Although they give approximate solutions, these techniques use no simplifying assumption and result in the final correct equilibrium state of the cable. Newton-Raphson method is used in this study. Formulas related to this technique are briefly explained below.

2.2 Cable Equilibrium Equations

A cable, having total unstressed length L_U and stressed length L_S, is supported between points A and B. The view of the cable in space is shown in Figure 2.1.

As illustrated in Figure 2.1, $\vec{P}_A$ and $\vec{P}_B$ are the position vectors of cable supports. Let M be any point on the cable defined by the following parameters;

l_u; unstressed arc length form point A to M.

l_s; stressed arc length from point A to M.

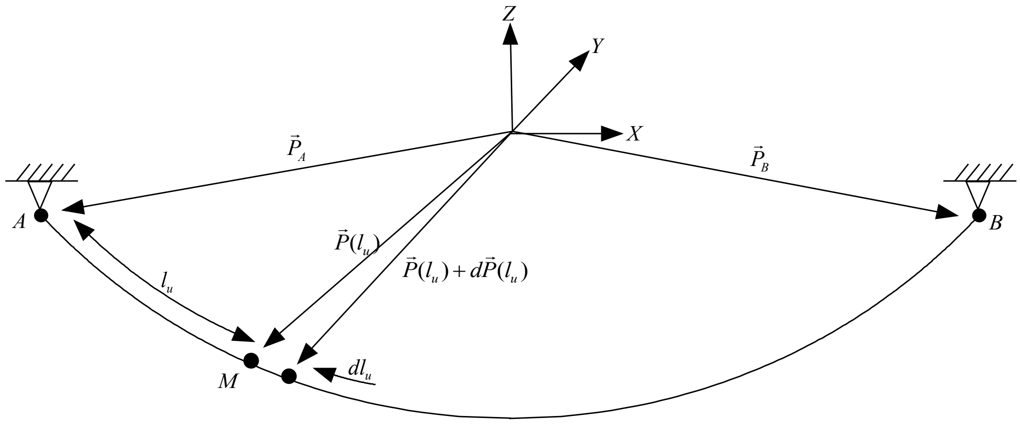

Figure 2.1 Configuration of single-segment cable in space.

The unit tangent along the cable, $\hat{\tau}(l_u)$, can be defined as;

$$\hat{\tau}(l_u) = \frac{d\vec{P}(l_u)}{dl_s} \tag{2.1a}$$

or

$$d\vec{P}(l_u) = -\hat{\tau}(l_u)dl_s \tag{2.1b}$$

The unknowns in Eq. 2.1b are; $\hat{\tau}(l_u)$ and the differential stressed arc length of the cable dl_s.

The unit tangent along the cable can also be defined as

$$\hat{\tau}(l_u) = \frac{\vec{R}(l_u)}{T(l_u)} \tag{2.2}$$

where $\vec{R}(l_u)$ is reaction vector at l_u , $T(l_u)$ is tension at l_u and dl_u is the original differential length of the cable.

So, the elongation of the differential element is

$$\Delta l_u = dl_s - dl_u \tag{2.3}$$

The strain of this element is the elongation divided by the original length.

$$\varepsilon(l_u) = \frac{dl_s - dl_u}{dl_u} \tag{2.4}$$

From Eq. 2.4 the stressed length of the element can be written as

$$dl_s = \left[1 + \varepsilon(l_u)\right] dl_u \tag{2.5}$$

Substituting Eq. 2.5 into Eq. 2.1b

$$d\vec{P}(l_u) = -\hat{\tau}(l_u)\left[1 + \varepsilon(l_u)\right] dl_u \tag{2.6a}$$

$$\frac{d\vec{P}(l_u)}{dl_u} = -\hat{\tau}(l_u)\left[1 + \varepsilon(l_u)\right] \tag{2.6b}$$

Finally, writing Eq. 2.6b in integral form

$$\vec{P}(l_u) = \vec{P}(0) - \int_0^{l_u} \frac{\vec{R}(x)}{T(x)}\left[1 + \varepsilon(l_u)\right] dx \tag{2.7a}$$

Since $\vec{P}(0) = \vec{P}_A$,

$$\vec{P}(l_u) = \vec{P}_A - \int_0^{l_u} \frac{\vec{R}(x)}{T(x)}\left[1 + \varepsilon(l_u)\right] dx \tag{2.7b}$$

Consequently, $\vec{R}_A$, which is equal to $\vec{R}(l_0)$, is the only unknown in this equation and it can be regarded as the initial condition of the problem.

2.3 Stiffness Matrix

If a virtual displacement, $\Delta\vec{P}_B$, is given to support B, there will be a change in the reactions at the other support, $\Delta\vec{R}_A$. The relation between these parameters are explained by the stiffness matrix, $\left[S\right]$.

$$\Delta\vec{R}_A = [S]\Delta\vec{P}_B \tag{2.8}$$

The stiffness matrix is determined by using the variational approach as follows:

From variation of Eq. 2.7b, $\Delta\vec{P}_B$ is determined.

$$\Delta\vec{P}_B = -\int_0^{L_U} \Delta\left\{[1+\varepsilon(l_u)]\frac{\vec{R}(l_u)}{T(l_u)}\right\}dl_u$$

$$= -\int_0^{L_U} \left\{\frac{1+\varepsilon(l_u)}{T(l_u)}\Delta\vec{R}(l_u) + \vec{R}(l_u)\Delta\frac{1+\varepsilon(l_u)}{T(l_u)}\right\}dl_u \tag{2.9}$$

Unknowns are $T(l_u)$, $\Delta\vec{R}(l_u)$ and $\Delta\frac{1+\varepsilon(l_u)}{T(l_u)}$ in Eq. 2.9.

$$\Delta\frac{1+\varepsilon(l_u)}{T(l_u)} = \frac{\Delta[1+\varepsilon(l_u)]T(l_u) - [1+\varepsilon(l_u)]\Delta T(l_u)}{T^2(l_u)}$$

$$= \frac{\Delta\varepsilon(l_u)T(l_u) - [1+\varepsilon(l_u)]\Delta T(l_u)}{T^2(l_u)} \tag{2.10}$$

Thus, unknowns are $T(l_u)$, $\Delta T(l_u)$, $\Delta\vec{R}(l_u)$, $\Delta\varepsilon(l_u)$ in Eq. 2.9.

Tension in cable is

$$T(l_u) = \left[\vec{R}(l_u)\bullet\vec{R}(l_u)\right]^{1/2} \tag{2.11}$$

In variational form, $\Delta T(l_u)$

$$\Delta T(l_u) = \frac{1}{2}\frac{\left[\vec{R}(l_u)\bullet\Delta\vec{R}(l_u) + \Delta\vec{R}(l_u)\right]}{\left[\vec{R}(l_u)\bullet\vec{R}(l_u)\right]^{1/2}} \tag{2.12}$$

Or

$$\Delta T(l_u) = \frac{\vec{R}(l_u)\bullet\Delta\vec{R}(l_u)}{T(l_u)} \tag{2.13}$$

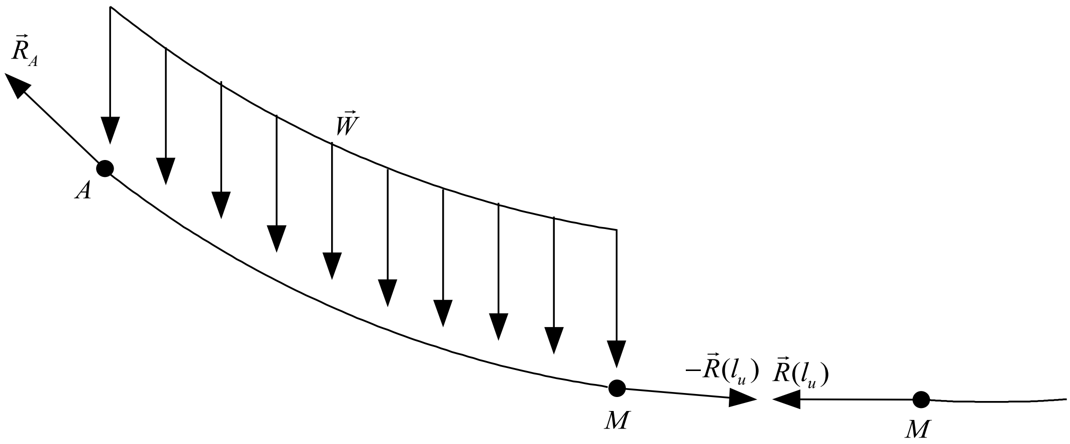

Figure 2.2 Reactions on cable

Many external forces e.g. wind force, could be applied to the cable. If no external load is applied, there will be only self-weight of the cable.

$$\vec{F}_{ext}(l_u) = \vec{W} l_u \tag{2.14}$$

From the free body diagram of cable element shown in Figure 2.2, reaction at point M is;

$$\vec{R}(l_u) = \vec{R}_A + \vec{F}_{ext}(l_u) \tag{2.15a}$$

For the whole cable

$$\vec{R}(L_U) = \vec{R}_A + \vec{F}_{ext}(L_U) \tag{2.15b}$$

$$\vec{R}_B = \vec{R}\left(L_U\right) \tag{2.16}$$

Substituting Eq. 2.16 into Eq. 2.15b

$$\vec{R}_B = \vec{R}_A + \vec{F}_{ext}\left(L_u\right) \tag{2.17}$$

From variation of Eq. 2.17

$$\Delta\vec{R}(l_u) = \Delta\vec{R}_A = \Delta\vec{R}_B \tag{2.18}$$

The strain can also be expressed by the stress-strain relationship as

$$\varepsilon(l_u) = \frac{T(l_u)}{EA}\upsilon \tag{2.19}$$

$T(l_u)$ is the tension at M and E, A and υ are material properties of cable.

The variational form of strain, $\Delta\varepsilon(l_u)$, from Eq. 2.4

$$\Delta\varepsilon(l_u) = \upsilon\left[\frac{T(l_u)}{EA}\right]^{\upsilon-1}\frac{\Delta T(l_u)}{EA} \tag{2.20a}$$

$$= \upsilon\varepsilon(l_u)\frac{\vec{R}(l_u)\bullet\Delta\vec{R}(l_u)}{T^2(l_u)} \tag{2.20b}$$

So, substituting Eq. 2.11 Eq. 2.13 and Eq. 2.20b into Eq. 2.10

$$\Delta\left[\frac{1+\varepsilon(l_u)}{T(l_u)}\right] = \frac{\upsilon\varepsilon(l_u)\dfrac{\vec{R}(l_u)\bullet\Delta\vec{R}(l_u)}{T^2(l_u)}T(l_u) - \left[1+\varepsilon(l_u)\right]\dfrac{\vec{R}(l_u)\bullet\Delta\vec{R}(l_u)}{T(l_u)}}{T^2(l_u)}$$

$$= -\frac{1+\left(1-\upsilon\right)\varepsilon(l_u)}{T^3(l_u)}\left[\vec{R}(l_u)\bullet\Delta\vec{R}(l_u)\right] \tag{2.21}$$

Finally, substituting Eq. 2.18 and Eq. 2.21 into Eq. 2.9

$$\Delta\vec{P}_B = -\int_0^{L_U}\left\{\left|\frac{1+\varepsilon(l_u)}{T(l_u)}\right|\Delta\vec{R}_A - \left|\frac{1+(1-\upsilon)\varepsilon(l_u)}{T^3(l_u)}\right|\left[\vec{R}(l_u)\bullet\Delta\vec{R}_A\right]\vec{R}(l_u)\right\}dl_u \tag{2.22}$$

In global coordinate directions Eq. 2.22 will be

$$\Delta P_{BX}\hat{i} = -\int_0^{L_U}\left[C_1\Delta R_{AX}\hat{i} - C_2C_3C_4\right]dl_u \tag{2.23a}$$

$$\Delta P_{BY}\hat{j} = -\int_0^{L_U}\left[C_1\Delta R_{AY}\hat{j} - C_2C_3C_4\right]dl_u \tag{2.23b}$$

$$\Delta P_{BZ}\hat{k} = -\int_0^{L_U} \left[C_1 \Delta R_{AZ}\hat{k} - C_2 C_3 C_4 \right] dl_u \tag{2.23c}$$

Where

$$C_1 = \left[\frac{1+\varepsilon(l_u)}{T(l_u)} \right]$$

$$C_2 = \left[\frac{1+(1-\upsilon)\varepsilon(l_u)}{T^3(l_u)} \right]$$

$$C_3 = \left[R_X(l_u)\Delta R_{AX} + R_Y(l_u)\Delta R_{AY} + R_Z(l_u)\Delta R_{AZ} \right]$$

$$C_4 = \left[R_X(l_u)\hat{i} + R_Y(l_u)\hat{j} + R_Z(l_u)\hat{k} \right]$$

Writing Eq. 2.23a,b,c in the form of Eq. 2.8

$$\begin{Bmatrix} \Delta P_{BX} \\ \Delta P_{BY} \\ \Delta P_{BZ} \end{Bmatrix} = \left[S \right]^{-1} \begin{Bmatrix} \Delta R_{AX} \\ \Delta R_{AY} \\ \Delta R_{AZ} \end{Bmatrix} \tag{2.24}$$

Where the stiffness matrix is

$$\left[S \right] = \begin{bmatrix} -\int_0^{L_e} \left[C_1 - C_2 R_X^2(l_u) \right] dl_u & -\int_0^{L_e} \left[C_2 R_X(l_u) R_Y(l_u) \right] dl_u & -\int_0^{L_e} \left[C_2 R_X(l_u) R_Z(l_u) \right] dl_u \\ -\int_0^{L_e} \left[C_2 R_Y(l_u) R_X(l_u) \right] dl_u & -\int_0^{L_e} \left[C_1 - C_2 R_Y^2(l_u) \right] dl_u & -\int_0^{L_e} \left[C_2 R_Y(l_u) R_Z(l_u) \right] dl_u \\ -\int_0^{L_e} \left[C_2 R_Z(l_u) R_X(l_u) \right] dl_u & -\int_0^{L_e} \left[C_2 R_Z(l_u) R_Y(l_u) \right] dl_u & -\int_0^{L_e} \left[C_1 - C_2 R_Z^2(l_u) \right] dl_u \end{bmatrix}$$

Inverse of stiffness matrix is the flexibility matrix, $\left[F \right] = \left[S \right]^{-1}$.

So, Eq. 2.8 can be rewritten as

$$\Delta P_B = \left[S\right]^{-1} \Delta R_A \tag{2.25a}$$

or

$$\Delta P_B = \left[F\right] \Delta R_A \tag{2.25b}$$

2.4 Newton-Raphson Method

The Newton-Raphson method is an iterative technique for solving equations numerically. The solution procedure of this method is based on making linear approximations to find a solution for nonlinear systems or equations in each step. It is aimed to achieve the target linearly. Nevertheless, solutions are always approximate. Newton-Raphson method is an appropriate method to find a solution for cable positioning due to its nonlinear behavior.

It will be seen that the position of cable is a function of $\vec{R}_A$ from Eq. 2.7b. However, the reaction at support A for the solution case, $\vec{R}_{A,sol}$, is not know. Newton-Raphson method is used to find that reaction. A linear approximation is made for each iteration to reach the solution.

The step-by-step procedure to find the unknown support reactions of cable is explained below and described schematically in Figure 2.3

1. Make an initial approximation for the reactions at support A, $\vec{R}_A^{[i]}$,where [i] shows the iteration number which is 0 for the initial guess.
2. Determine the cable configuration by Eq. 2.7b. The end of the cable position is $\vec{P}^{[i]}\left(L_U\right)$. Also calculate the stiffness matrix $\left[S^{[i]}\right]$.
3. Determine the misclose vector and the error as

$$\vec{M}^{[i]} = \vec{P}_B - P^{[i]}(L_U) \tag{2.27}$$

$$E^{[i]} = \left| \vec{M}^{[i]} \right| \tag{2.28}$$

4. Calculate a better approximation for the support reactions at A.

$$R_A^{[i+1]} = R_A^{[i]} + \left[S^{[i]} \right]^{-1} \vec{M}^{[i]} \tag{2.29}$$

5. Go to step 2 and continue iterations until $E^{[i]} \leq ERR$. where ERR is the target error for approximate result.

It can be easily comprehended that initial guess for the support reactions is an important step. A convenient initial support reaction will decrease the iteration number considerably.

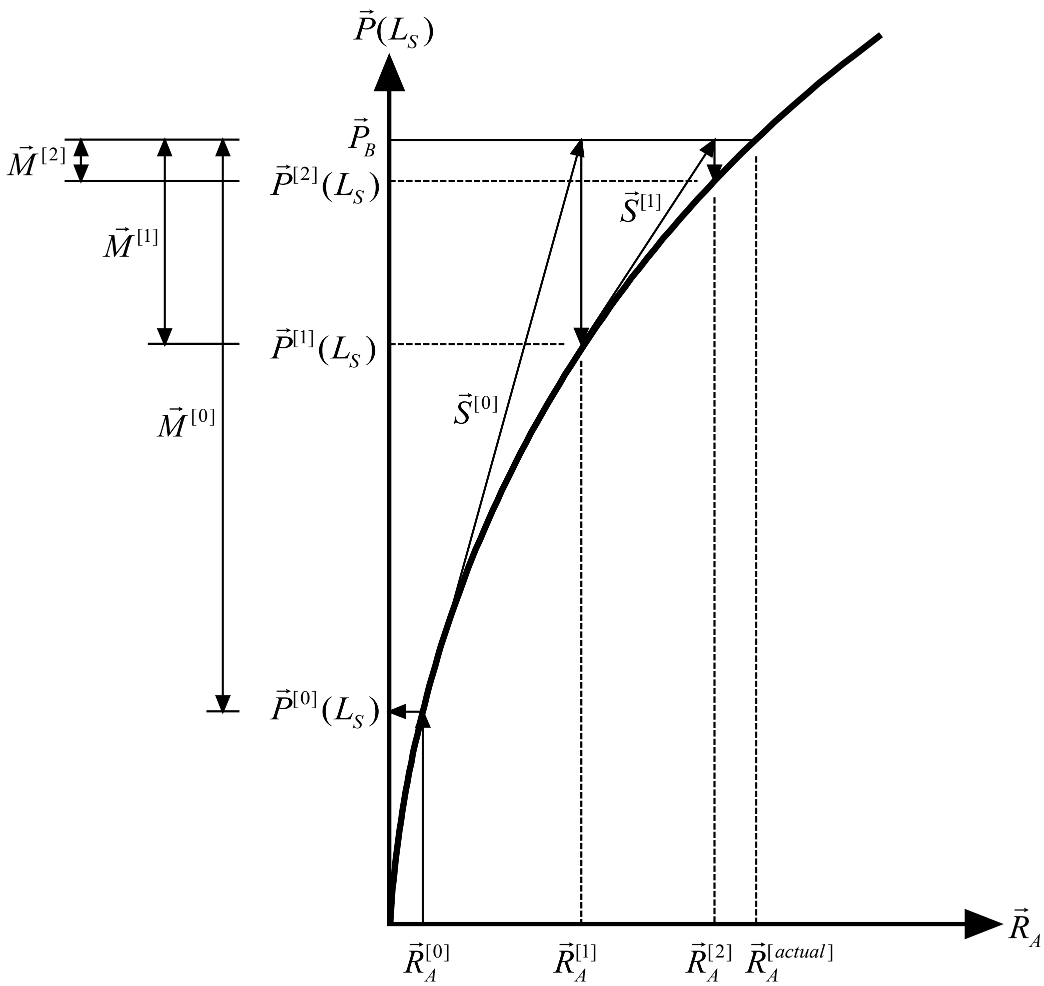

Figure 2.3 Newton Raphson Method in schematic form for single segment cable.

CHAPTER 3

MULTI-SEGMENT CONTINUOUS CABLE

3.1 General

Similar to continuous beams, multi-segment continuous cables are monolithic cables with multiple intermediate supports. It is assumed that the intermediate supports are also stationary but the cable is free to slide over them without facing any frictional resistance. There is a continuous interaction between the segments and a continuous load path along the cable when it is loaded. As a result, the final equilibrium configuration and the resulting stresses under loading are controlled by the behavior of each segment. Therefore, the solution algorithm of previous chapter for a single cable segment can also be used iteratively for the analysis of multi-segment continuous cables. For this purpose, the cable segments are divided into a number of elements and each segment is analyzed as an independent single-segment cable. The stress continuity requirement between the adjacent cable segments is enforced in each iteration until complete equilibrium is reached. The equilibrium state is reached when the stress discontinuity between the adjacent segments is less than a preset small value.

The only unknowns for the multi-segment continuous cable are the unstressed lengths of each cable segment between the successive supports. In general, a predictive/corrective iterative algorithm is employed for the nonlinear analysis. In each iteration, a predictive solution is obtained based on the initially assumed distribution of the unstressed length of cable between its segments. The unbalanced reactions or cable tension at each internal support are then used in the corrective step for a corrected distribution of cable length among the segments. If the reaction or cable tension differences are reasonably small, the equilibrium state is said to be reached for the given segment length distribution. Otherwise, prediction / correction iterations are continued. Two alternative schemes are employed in this study for the correction iterations. These are explained below.

3.2 Direct stiffness approach

A cable having an unstressed length L_U and stressed length L_S is suspended between two fixed supports at its ends and supported by a number of stationary roller supports in between, as illustrated in Figure 3.1

In the equilibrium state of the cable, the stressed and unstressed lengths of its i^th segment are denoted by $l_{s(i)}$ and $l_{u(i)}$, respectively.

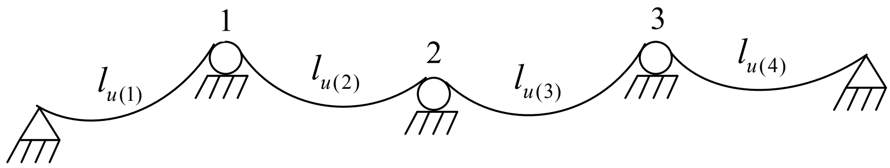

Figure 3.1 Configuration of multi-segment continuous cable.

Therefore,

$$L_U = \sum_{i=1}^{n} l_{u(i)} \tag{3.1a}$$

$$L_S = \sum_{i=1}^{n} l_{s(i)} \tag{3.1b}$$

where; "n" is the number of segments in the continuous cable system.

In general, a predictive solution based on the initially assumed distribution of the total unstressed cable length between its segments leads to some unbalanced reactions or cable tensions at internal supports unless the system is in complete equilibrium. The situation is shown in Figure 3.2 for support i where the unbalanced reactions and cable tensions are

$$\Delta\vec{R}_{(i)} = \vec{R}_{F(i+1)} - \vec{R}_{L(i)} \tag{3.2a}$$

$$\Delta T_{(i)} = \left|\vec{R}_{F(i+1)}\right| - \left|\vec{R}_{L(i)}\right| \tag{3.2b}$$

in which

$\vec{R}_{F(i+1)}$ is the cable tension vector at start node of segment i+1

$\vec{R}_{L(i)}$ is the cable tension vector at end node of segment i

$\Delta\vec{R}_{(i)}$ is the unbalanced reaction vector at support i

$\Delta T_{(i)}$ is the unbalanced cable tension at junction of cable segments (support i)

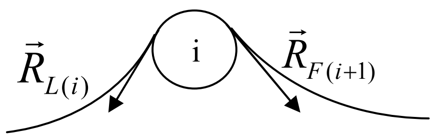

Figure 3.2 Reactions (cable tensions) at support i.

However, there is always a set of unstressed length adjustments $\{\Delta L_U\}$ between the neighboring segments which will bring the cable system into complete equilibrium. Each of the unstressed length adjustment, $\Delta L_{U(i)}$, is such that at any support i where the cable segments i and i+1 are attached

$$\Delta L_{U(i)}^{segment} = -\Delta L_{U(i)} \tag{3.3a}$$

$$\Delta L_{U(i+1)}^{segment} = \Delta L_{U(i)} \tag{3.3b}$$

$$\Delta L_{U(i)}^{segment} + \Delta L_{U(i+1)}^{segment} = 0 \tag{3.3c}$$

in which $\Delta L_{U(i)}^{segment}$ and $\Delta L_{U(i+1)}^{segment}$ are the changes in unstressed lengths of segments i and i+1, respectively, and $\Delta L_{U(i)}$ is the adjustment applied to cable segments at support i.

In the course of iterative solution process for the equilibrium state of cable system, there is always a need for some correction in the currently assumed distribution of total cable length among its segments. This is necessary to move closer to the equilibrium state by minimizing the unbalanced reactions between cable segments. It can be achieved, if a quasi-linear behavior of the system is assumed at the end of each predictive solution step. With this assumption, we can set up a relationship between the anticipated unstressed length adjustment $\delta L_{U(j)}$ at any support j and the corresponding change it would create in the unbalanced reactions at support i. This change in unbalanced reactions, $\delta T_{(i)}$, can be expressed as follows

$$\delta T_{(i)} = K_{ij} \cdot \delta L_{U(j)} \tag{3.7a}$$

or in a matrix form for adjustments at all internal supports as

$$\{\delta T\} = [K] \cdot \{\delta L_U\} \tag{3.7b}$$

where

$$\{\delta T\} = \begin{Bmatrix} \delta T_{(1)} \\ \delta T_{(2)} \\ \vdots \\ \delta T_{(n)} \end{Bmatrix}$$

$$\{\delta L_U\} = \begin{Bmatrix} \delta L_{U(1)} \\ \delta L_{U(2)} \\ \vdots \\ \delta L_{U(n)} \end{Bmatrix}$$

$$K = \begin{bmatrix} K_{11} & \cdots & K_{1n} \\ \vdots & \ddots & \vdots \\ K_{n1} & \cdots & K_{nn} \end{bmatrix}$$

and the coefficient matrix $[K]$ can be regarded as a stiffness matrix with each term K_{ij} giving the change in unbalanced reactions, $\delta T_{(i)}$, at support i due to a change in unstressed length $\delta L_{U(j)}$ at support j between cable segments j and j+1.

The tangential stiffness matrix $[K]$ in Eq. 3.7b can be constructed column-by-column by adjusting the unstressed lengths of cable segments at support j by a small amount δL and calculating the resulting changes in the unbalanced reactions at all support locations from the reanalysis of the cable system with the changed segment lengths at support j. The j$^{\text{th}}$ column of $[K]$ is then obtained as

$$K_{ij} = \delta \Delta T_{(i)} / \delta L \qquad (i = 1, 2, ..., n) \tag{3.8}$$

In the correction step, the objective is to find the required amount of length adjustment at each support to eliminate the current values of unbalanced reactions at supports. This is obtained from Eq. 3.7b as

$$\{\Delta L_U\} = [K]^{-1} \cdot \{\Delta T\} = [F] \cdot \{\Delta T\} \tag{3.9}$$

where the matrix $[F]$ can be regarded as a kind of flexibility matrix giving the changes in cable segment lengths for a set of axial forces applied along the cable at internal supports (segment junctions). If the cable behavior were linear as assumed, the length adjustments $\{\Delta L_U\}$ of Eq. 3.9 would eliminate the unbalanced reactions at internal supports and bring the cable system into true equilibrium. However, in general, this will not be the case since the cable behavior is nonlinear and some additional iterations will be needed before reaching the final equilibrium. Therefore, Newton-Raphson iterations are continued in this predictive/corrective algorithm to reach the final equilibrium state.

3.3 Relaxation (tension distribution) method

A relaxation approach similar to moment distribution method commonly used for the analysis of continuous beams can also be used for the nonlinear analysis of multi-segment continuous cables. This is a special form of the stiffness method described above. The basic difference is in the way the cable segment lengths are adjusted for a better approximation to equilibrium state. In the direct stiffness method, the influence of segment length adjustment at a joint on every other joint is calculated first. Hence, a coupled coefficient matrix is constructed for length adjustments and the adjustment is applied at all joints simultaneously. Whereas, in the tension distribution approach, the length adjustments are introduced at each internal support, in turn, while keeping all other segment lengths as they are. Therefore, in the corrective stage following a predictive solution, an influence (stiffness) coefficient is calculated at a selected joint first by introducing a virtual adjustment at the joint and the actual amount of adjustment required to eliminate the unbalanced reaction at the joint is determined based on this information. The procedure is repeated cyclically for all internal joints until an equilibrium state is reached where the unbalanced reactions at internal supports become negligibly small.

Cable system is analyzed joint by joint at internal supports where cable segments meet. Therefore, the set of equations in Eq. 3.9 reduces to a single equation as;

$$\Delta L_U = f \cdot \Delta T \tag{3.10}$$

where the unbalanced cable tension at the junction, ΔT, is as defined in Eq.3.2b. and the joint flexibility coefficient f can be found from Eq. 3.8 as

$$f = \delta L / \delta \Delta T \tag{3.11}$$

Eq. 3.10 is used for each roller support to calculate the require amount of adjustments. As explained in direct stiffness approach, the adjustments applied will not yield the solution due to nonlinear characteristic of the cable. Therefore, Newton-Raphson iterations are still needed to reach the final equilibrium state of the system.

3.4 Newton-Raphson iterations

The unknowns for the multi-segment continuous cables are the unstressed lengths for the segments. Therefore, equilibrium state can be reached by adjusting the length of each segment so that the unbalanced reactions at internal joints (supports) are minimized.

Assuming some initial lengths $l_{u(i)}^{[0]}$ for each segment turns the multi-segment continuous cable into a set of independent single-segment cables with stationary end points. Newton-Raphson iterations are performed by assuming a linear behavior after each cycle of Direct Stiffness or Tension Distribution calculations. This is continued until an equilibrium state of cable segments is reached at which the unbalanced reactions at all segment junctions are negligibly small.

The procedure is explained schematically in Figure 3.3 and its steps can be summarized as follows.

Assume a set of initial values, $l_{u(i)}^{[m]}$, for the unstressed length of cable segments where m is the iteration number starting with m=0 for the first iteration.

1. For a predictive solution, analyze each cable segment as an independent structure and determine the error or the unbalanced reaction (cable tension) at every junction i as

$$E_{(i)}^{[m]} = \left|\Delta T_{(i)}^{[m]}\right| \qquad (3.12)$$

2. Stop Newton-Raphson iterations if the unbalanced cable tension of Eq. 3.12 at all junctions is less than a preset error tolerance, *ERR*. Otherwise, continue with the following correction step.

3. Determine the amount of length adjustment, $\Delta L_{U(i)}$, to be applied at each junction by using either the Direct Stiffness or the Tension Distribution approach. and apply the segment length corrections as.

$$l_{u(i)}^{[m+1]} = l_{u(i)}^{[m]} \mp \Delta L_{U(i)} \qquad (3.13a)$$

$$l_{u(i)}^{[m+1]} = l_{u(i)}^{[m]} + \Delta L_{U(i)}^{segment} \qquad (3.13b)$$

and go to Step 2.

Plus or minus signs in Eq. 3.13a imply that if the unstressed length of cable segment i is increased, that of the next segment i+1 is decreased by the same amount. This way, the total unstressed length of cable system remains unchanged.

Note that choosing the starting values for the unstressed length of each segment is a crucial step. A good distribution of the cable length among its segments will decrease the number of iteration considerably.

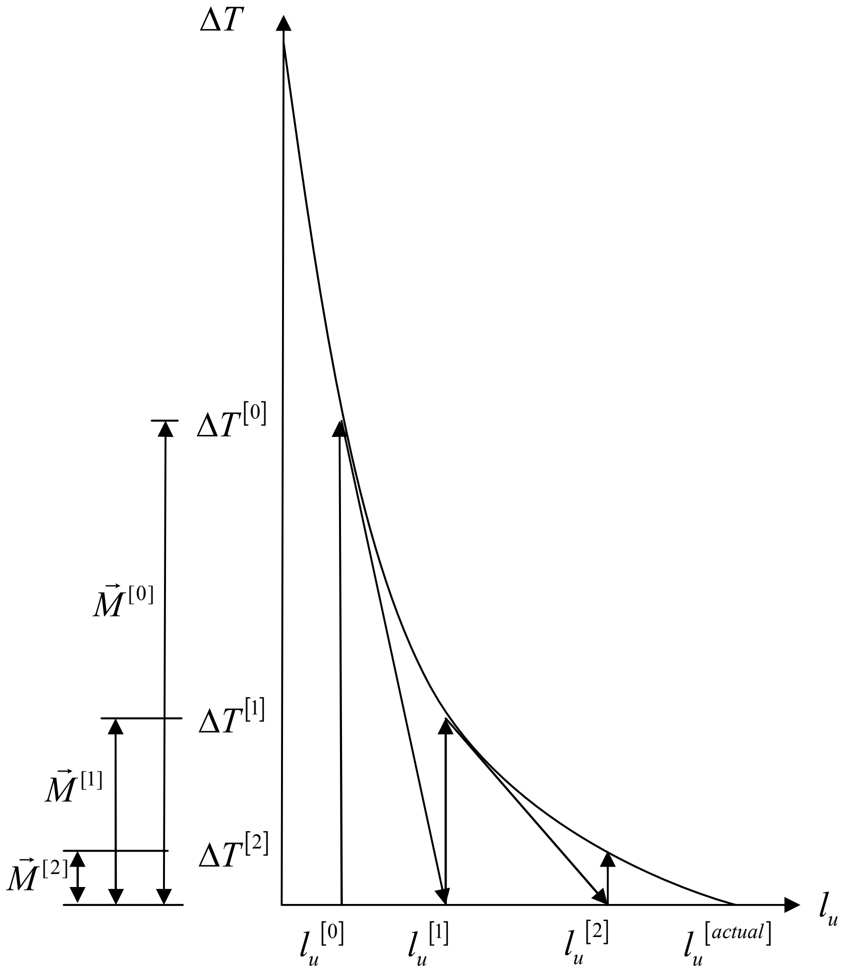

Figure 3.3 Newton Raphson method in schematic form for multi segment continuous cable.

3.5 Comparison of Direct Stiffness and Relaxation Approaches.

In essence, both procedures described above can be used for the solution of multi-segment continuous cables. They lead to an equilibrium state after a number of iterations. However, as far as their effectiveness is concerned, there are certain circumstances under which one of them is more effective than the other.

Tension distribution method is a discrete calculation method. A correction is applied though a length adjustment at a joint to reduce the reaction imbalance at the relevant support. The adjacent equilibrium states of cable segments are then recalculated. After repeating similar length adjustments and calculations at all other internal support locations, one round of calculations will be completed. At this point, the cable system will be closer to its final equilibrium state. However, in general, the cable system as a whole will not be in equilibrium since the correction applied at one joint will upset the possible equilibrium state at the far ends of the cable segments involved. Therefore, this predictive/corrective algorithm is applied cyclically at all joints one by one until convergence is achieved at all support locations. On the other hand, length adjustments in the correction phase are all applied simultaneously in the Direct Stiffness approach. Then, all segments are reanalyzed and the convergence is checked in the predictive phase for the next iteration.

Normally, if the length of a tight cable is decreased for a given segment, the end reactions will increase. However if the length of a very slack cable is decreased, the end reactions may also decrease. A cable having a changing length is supported between two fixed supports will have minimum support reactions for a specific length and the corresponding degree of slackness. The term very slack cable refers to a cable with a degree of slackness beyond this limit. Therefore, based on this limit state and for the purpose of analysis, a cable can be classified as either a tight or slack cable or a very slack cable. These explanations could be easily seen in Figure 3.4. Curvature in Figure 3.4 is obtained for a cable having 0.05m diameter supported at (0,0,0), (0,50,0) coordinates.

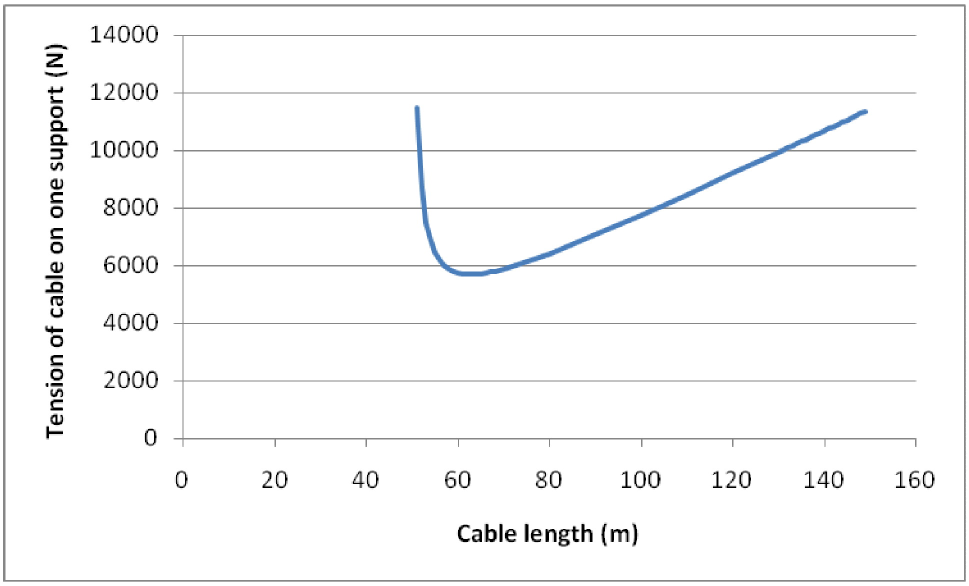

Figure 3.4 Typical slackness curve of a cable

Whether the Direct Stiffness or the Tension Distribution approach is used, a common difficulty encountered in the analysis of slack cable systems is the overshooting problem. The problem comes up when a cable segment turns into very slack cable condition or just on the limit state in any iteration phase. In this case, the predicted amount of length adjustment to be applied on these segments may become excessively high since the calculations are based on the joint stiffnesses and assumption of quasi-linear behavior of cable. This leads to oscillations between very large corrections in either direction and finally divergence of the prediction/correction iterations. In order to avoid the occurrence of such situations a damping ratio of 0.5 is used in the correction step and half of the predicted corrections are applied at the joints.

Although this damping ratio decreases the occurrence of those extreme situations, it is still possible to see an extreme situation for some cable systems. So, corrections should be checked in each iteration not to create a cable with a negative length. Corrections are checked and revised for each joint in Tension Distribution method. However, this revision is not possible for Direct Stiffness method, because Direct Stiffness method finds corrections for the whole system. Therefore, if a problem is encountered at a joint, revision of that joint correction should be distributed to all segments. However, this could lead to problems at other joints and so on.

Stiffness matrix of the system will not be suitable if any one of the segments with the highest degree of slackness turns into very slack cable state or around the limit state in any iteration phase of calculation. Therefore stiffness method, which makes calculations with the stiffness matrix of the whole system, is not appropriate for systems which can have very slack cable segments. Tension distribution method is better suited for such cable systems.

At the onset of analysis there are two options to choose as a solution procedure. One choice is to start with the Direct Stiffness approach and switch to Tension Distribution if a problem with the stiffness matrix and so corrections is detected. Another choice is to decide on the degree of slackness of the cable system first before proceeding with the initial cycle of corrections and continue accordingly. If preliminary calculations reveal that the degree of slackness of multi-segment continuous cable is less than a preset limit, the Direct Stiffness approach is utilized. Otherwise, the subsequent iterations are continued with the Tension Distribution approach.

Determination of the degree of slackness is not possible for multi segment continuous cables although it is possible for single segment cables. Because corrections and/or cable distribution to segments is not known in any iteration as described above. In the software developed in this study for the analysis of multi-segment continuous cable systems, CABPOS, the following approach is taken. Given the total unstressed length of cable and the location of the support points, the total length is distributed among the segments in proportion to their spans. An unstressed length higher than 10% of the span is used as a limiting value for system to regard it as a very slack cable This limit for the classification of a cable system as very slack for the purpose of analysis appears to be a reasonable and safe value since no difficulties are encountered with this assumed limit in the various sample analyses carried out for verification.

The algorithm explained above for the solution of multi-segment continuous cables is implemented in a FORTRAN program called CABPOS and used for the analysis of a set of multi-segment continuous cable systems for verification.

CHAPTER 4

VERIFICATION FOR SINGLE-SEGMENT CABLES

4.1 General

Multi-segment continuous cable analysis algorithm is first used for the solution of some single-segment cables for verification. The results obtained by the program CABPOS are compared with those obtained by the widely used commercial finite element program ANSYS [19]. The input data for ANSYS program of the sample single-segment cable system is given in Appendix B1. The cable is analyzed in five different configurations in space using a range of mesh densities. The final support reactions and the cable geometry are used for comparison.

A numerical iterative algorithm is proposed for the solution of cable systems. Consequently, the predicted solution will only be an approximation to the exact equilibrium state. Therefore, the convergence characteristic of the algorithm as well as its ability to produce the final equilibrium state accurately is of concern. The convergence characteristic of the algorithm is verified by changing the cable configuration in space and its degree of slackness. The accuracy of the predicted results is checked by the mesh density used for the cable.

4.2 Description of the Problem

- Material properties of cable

  Density of the cable : 7.85E3 kg/m^3

  Modulus of elasticity : 200E9 N/m

  Thermal expansion coefficient : 1.2E-5 / ºC

- Physical properties of cable ;

  Total cable length : 18 m

  Diameter of cable : 0.05 m

- Environmental properties

  Temperature change : +40 ºC

- Program constraint

  Precision : 1E-6 m (ERR, the target error)

There are five different cable configurations. One of them is tight and the others are slack cables. Support locations are given in Table 4.1. One end of cable is supported at point A and other end is supported at point B. Each cable is solved for a range of mesh densities of 50, 100, 250, 500, 1000 and 10000 elements.

Table 4.1 Support locations

Supports	X coordinate (m)	Y coordinate (m)	Z coordinate (m)
A	0.0	0.0	0.0
B1	10.0	0.0	10.0
B2	9.0	3.0	11.0
B3	11.0	6.0	9.0
B4	11.0	9.0	11.0
B5	11.0	9.1	11.0

4.3 Solution by CABPOS

Data related with cable supported at A and B3 will be given in this section. Other solutions will not be shown.

Final coordinates, length and reactions of cable A-B3 are shown in Table 4.2, Table 4.3, Table 4.4, Table 4.5, Table 4.6 and Table 4.7.

Table 4.2 Data for cable A-B3 solved with 50 elements.

Number of finite elements	50	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999994
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999996
Reactions (N)	1269.62	2216.84
Final Cable Length (m)	18.0087	

Table 4.3 Data for cable A-B3 solved with 100 elements.

Number of finite elements	100	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999992
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999993
Reactions (N)	1277.81	2204.86
Final Cable Length (m)	18.0087	

Table 4.4 Data for cable A-B3 solved with 250 elements.

Number of finite elements	250	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999991
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999993
Reactions (N)	1282.75	2197.66
Final Cable Length (m)	18.0087	

Table 4.5 Data for cable A-B3 solved with 500 elements.

Number of finite elements	500	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999991
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999993
Reactions (N)	1284.39	2195.25
Final Cable Length (m)	18.0087	

Table 4.6 Data for cable A-B3 solved with 1000 elements.

Number of finite elements	1000	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999991
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999993
Reactions (N)	1285.22	2194.05
Final Cable Length (m)	18.0087	

Table 4.7 Data for cable A-B3 solved with 10000 elements.

Number of finite elements	10000	
Supports (m)	A(0,0,0)	B3(11,6,9)
X Coordinate (m)	0	10.9999991
Y Coordinate (m)	0	6.0000003
Z Coordinate (m)	0	8.9999992
Reactions (N)	1285.97	2192.96
Final Cable Length (m)	18.0087	

The reaction data of cable A-B3 can be seen in Table 4.8.

Table 4.8 Support reactions for A-B3 given by CABPOS.

A-B3		
Number of elements	First Support Reaction (N)	Second Support Reaction (N)
50	1269,62	2216,84
100	1277,81	2204,86
250	1282,75	2197,66
500	1284,40	2195,53
1000	1285,22	2194,05
10000	1285,97	2192,96

The convergence of the solution of cable A-B3 for different number of elements is shown in Figure 4.1 and Figure 4.2.

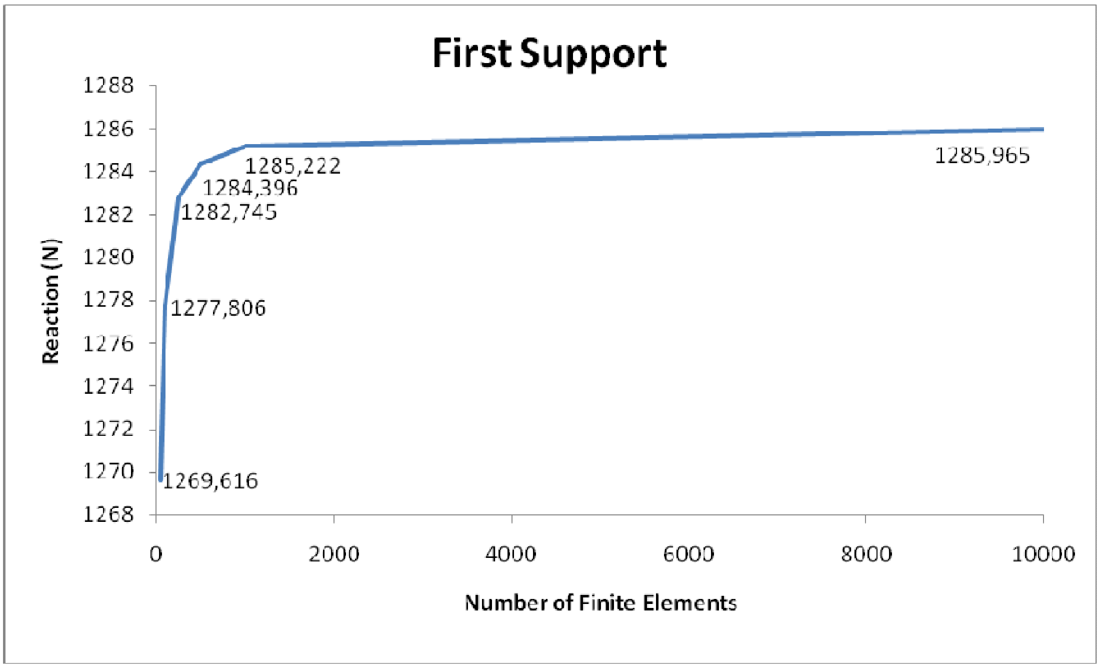

Figure 4.1 Reactions at first support given by CABPOS.

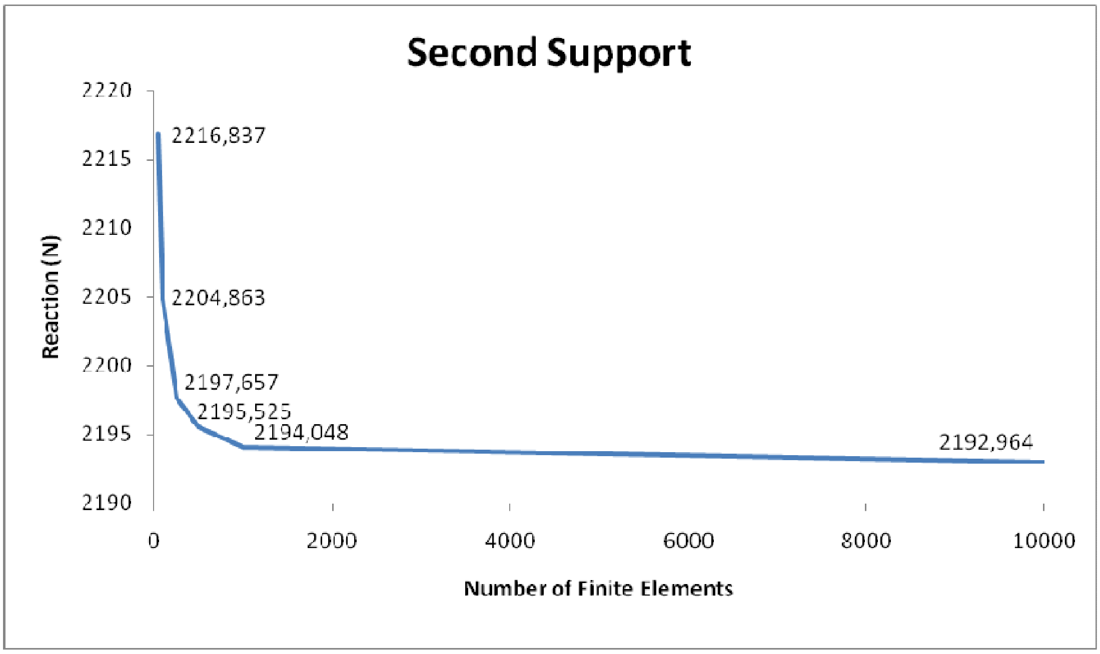

Figure 4.2 Reactions at second support given by CABPOS.

It is seen in above figures that, reactions at supports converge to a value. There is a 0.6% error between 50 and 100 element solution. However, between 1000 and 10000 element solution, 0.06% error occurs. So, if this trend goes on, there would probably be a 0.005% error for 100000 elements. Although it will converge a little to the real value for reaction, this solution does not change reaction a lot.

4.4 Solution by ANSYS

ANSYS solve the problem as continuum between the end supports. Therefore, the cable ends are always coincident with the supports.

Support reactions of cable A-B3 for different number of elements are given in Table 4.9

Table 4.9 Support reactions for cable A-B3 given by ANSYS.

A-B3		
Number of Elements	First Support Reaction (N)	Second Support Reaction (N)
50	1285,97	2192,70
100	1286,03	2192,84
250	1286,04	2192,85
500	1286,05	2192,86
1000	1286,05	2192,86
10000	1286,05	2192,86

The convergence of the solution for different number of elements can be seen in Figure 4.3 and Figure 4.4.

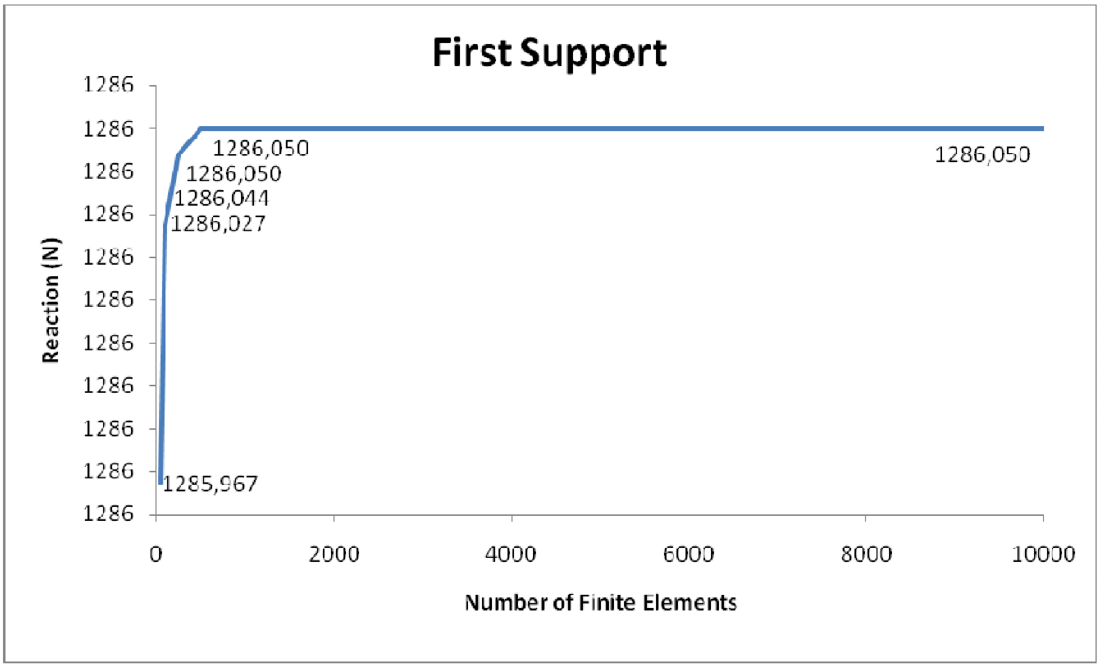

Figure 4.3 Reactions at first support given by ANSYS.

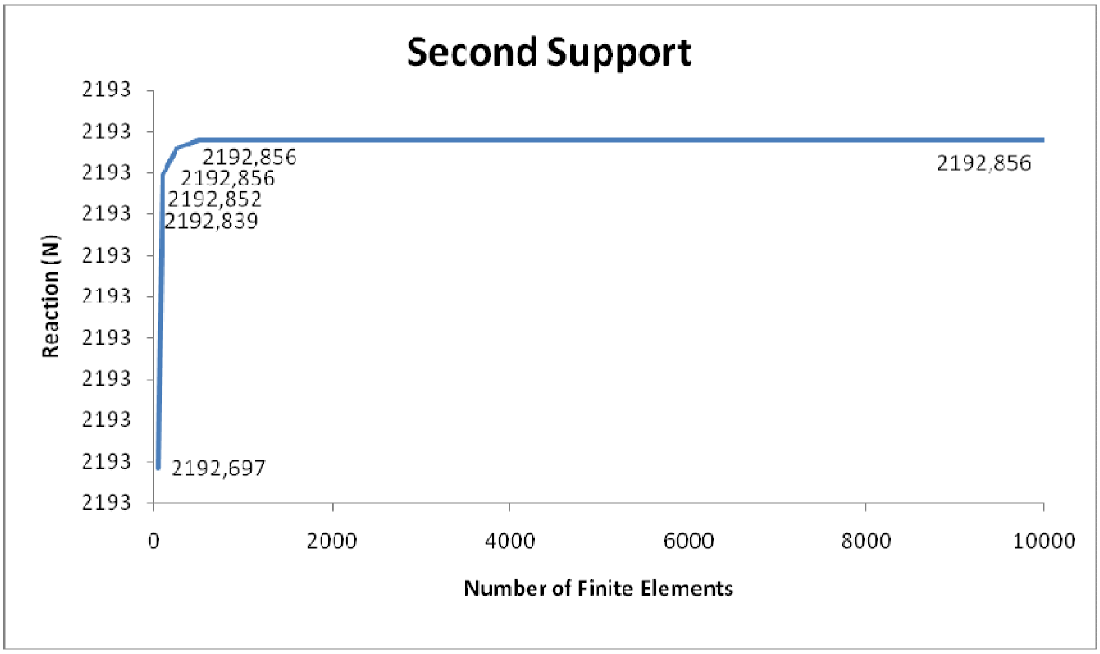

Figure 4.4 Reactions at second support given by ANSYS.

ANSYS gives approximately the correct results with a reasonable number of elements. Slope of the convergence curve is zero from 1000 to 10000 elements, as shown above. Zero slope means that there is no need to further refine the element mesh.

4.5 Comparison of results

Comparison of solutions is made on reaction difference as said above. The comparison could be made in a lot of different ways. However, stresses have much importance for structural systems.

Convenient number of elements should be selected for each problem. It could be made in a way that changing mesh density and comparing the results gotten from each. 10000 elements is used for this problem, because, there won't be much change in result for further increase in finite element number.

Reaction results of each five configuration having 10000 elements are sorted in Table 4.10.

Table 4.10 Reaction results for different configurations.

10000 elements		First Support Reaction (N)	Second Support Reaction (N)
B1	CABPOS	1613,27	1613,50
	ANSYS	1613,42	1613,42
B2	CABPOS	1416,98	1870,60
	ANSYS	1417,06	1870,50
B3	CABPOS	1285,97	2192,96
	ANSYS	1286,05	2192,86
B4	CABPOS	9993,01	11353,20
	ANSYS	9993,24	11353,40
B5	CABPOS	302203,43	303577,66
	ANSYS	302371,56	303744,94

Related error of percentages are tabulated in Table 4.11.

Table 4.11 Error of percentages for single-segment cable solutions.

Configurations	First support error	Second support error	Maximum error
A-B1	0,010%	0,005%	0,010%
A-B2	0,006%	0,006%	0,006%
A-B3	0,007%	0,005%	0,007%
A-B4	0,002%	0,002%	0,002%
A-B5	0,056%	0,055%	0,056%

It could be easily seen that there is very little difference between the solutions of CABPOS and ANSYS. Average of maximum error of this problem is approximately 0.02%. It is known that both programs made errors related with finite element number and rounding off. Another known matter is that structural systems are not exquisite. So, 0.02% error is enough approximation for this type of problems.

Profile of cable A-B3 is given in **Error! Reference source not found.** by the coordinates obtained from both programs CABPOS and ANSYS.

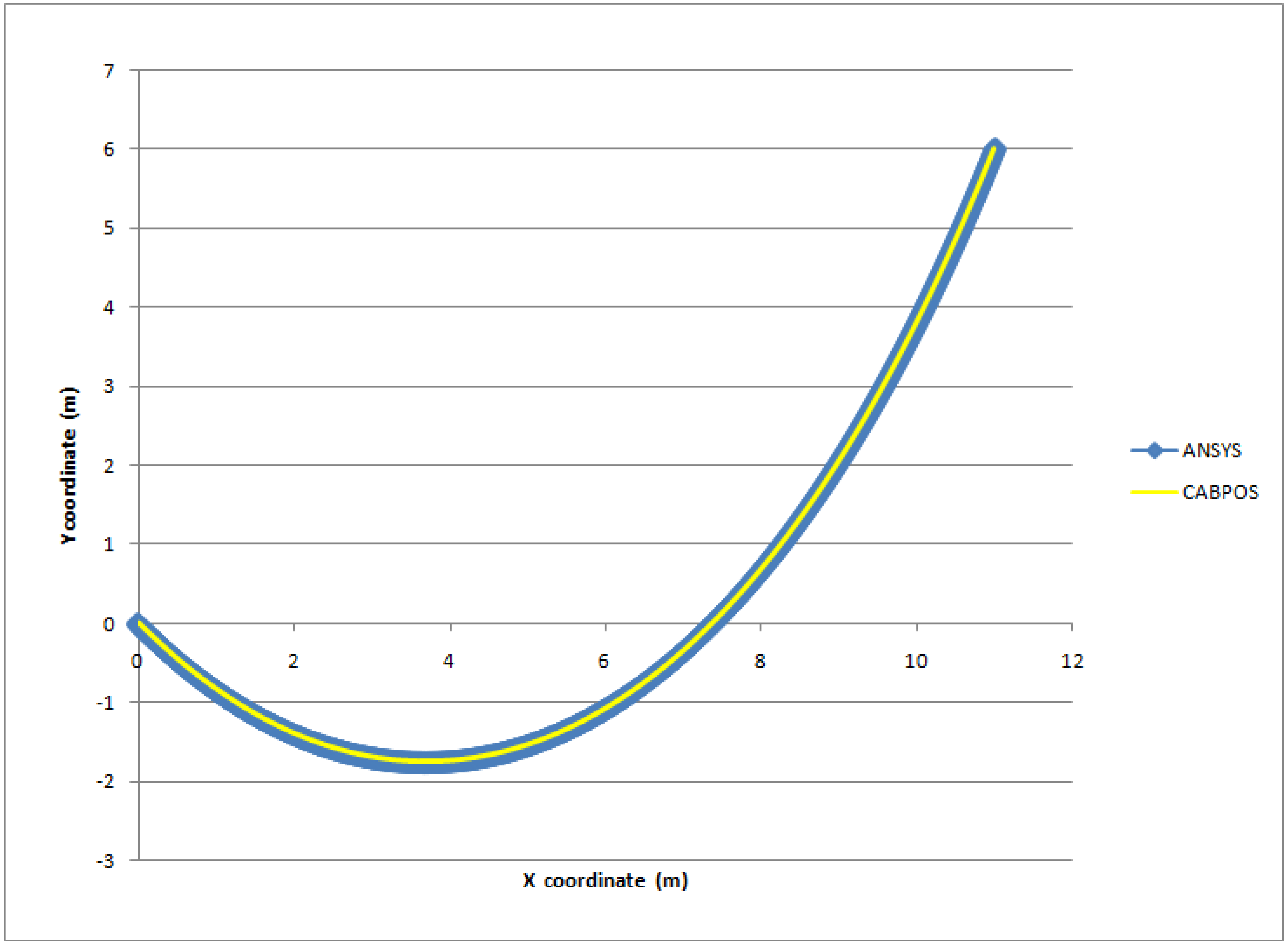

Figure 4.5 Profile of cable A-B3

CHAPTER 5

VERIFICATION FOR MULTI-SEGMENT CONTINUOUS CABLES

5.1 General

The solution methods for multi-segment continuous cable are explained in Chapter 3. According to these methods, if single-segment cable solution of CABPOS is correct or approximately correct, the multi-segment continuous cable solution can be verified by solving cable segment by segment. Reactions of each segment could be found by single-segment cable solution of CABPOS with the lengths found from multi-segment solution of CABPOS. Thus, reactions of successive segments can be compared whether they are same. Although this technique could be called a valid verification, ANSYS is used for verification.

Problem is solved in ANSYS by using contact elements. These contact elements have zero tangent stiffness. Thus, these contacts could be classified as roller supports. Monolithic cable is modeled as fixed supported at both ends and roller supports are defined between these fixed supports. Different cable configurations are obtained by displacing the one end of cable. Code of the program written in ANSYS is given on Appendix B2.

The verification of multi-segment continuous cable solution is made on support reactions as made in single-segment verification. All contact reactions and fixed support reactions are compared.

5.2 Description of Problem

Cable having 0.05 m diameter was used in single-segment solution verification. Cable is assumed 0.02 m diameter having an ice cover through the cable for multi-segment continuous cable verification. The ice cover has a 0.05 diameter from the center of the cable. So, this ice cover gives an extra load. This extra load is applied by increasing density of cable which corresponds to 4 times density of steel.

- Material properties of cable ;

Weight of the cable	: 4*7.85E3 kg/m^3	(including ice)
Modulus of elasticity	: 200E9 N/m	
Thermal expansion coefficient	: 1.2E-5 / ºC	

- Physical properties of cable ;

Total cable length	: 76.2 m
Diameter of cable	: 0.02 m

- Environmental properties ;

Thermal change	: +40 ºC

- Program constraint ;

Precision	: 1E-6 m	(ERR, the target error.)

There are 3 different cable configurations. One of them is tight and others are slack cables. These different cable configurations are obtained by giving displacement to one end of the cable. Coordinates of supports are shown in Table 5.1

Solutions of three different cable configurations are made for different number of finite elements which are 100, 500, 1000 and 5000. Data related with cable supported at F1 and F2c will be shown on this section.

Table 5.1 Coordinates of supports.

Supports	Coordinates (m)		
	X	Y	Z
F1	0	0	0
R1	10	-1	0
R2	20	-3	0
R3	30	-6	0
R4	40	-10	0
R5	50	-15	0
R6	60	-21	0
F2a	70	-21	0
F2b	70	-27	0
F2c	70	-28	0

5.3 Solution of CABPOS

The reaction data of cable F1- F2c solved by CABPOS can be seen in Table 5.2.

Table 5.2 Support reactions of cable F1-F2c given by CABPOS.

F1-F2c					
Number of elements		100	500	1000	5000
Support reactions (N)	F1	224218,18	224219,66	224219,83	224219,97
	R1	22846,55	22854,39	22855,37	22856,15
	R2	22007,92	22015,76	22016,74	22017,52
	R3	20861,23	20869,06	20870,04	20870,82
	R4	19509,22	19517,046	19518,02	19518,80
	R5	18051,54	18059,36	18060,33	18061,11
	R6	16571,70	16579,51	16580,49	16581,27
	F2c	221520,18	221521,53	221521,69	221521,81

The convergence of the solution for different mesh densities is shown in Figure 5.1. Sum of the reactions vs. number of finite elements is graphed instead of showing graph for each support.

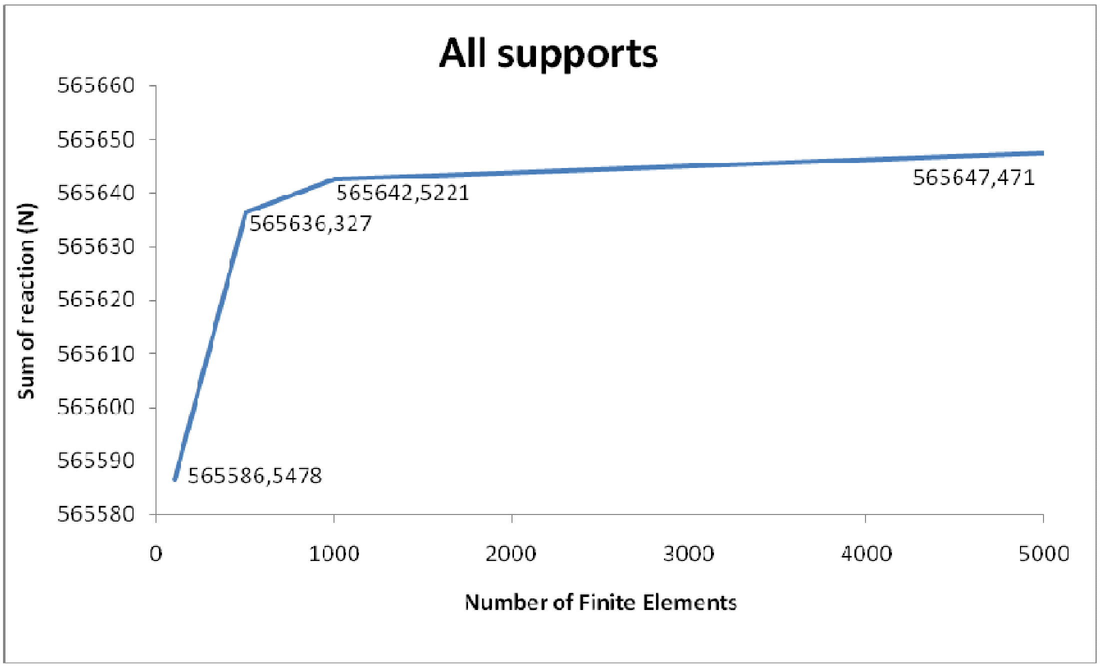

Figure 5.1 Sum of support reactions for cable F1-F2c given by CABPOS.

The reaction difference between 1000 and 5000 element solution is approximately 5 N. This difference corresponds to 0.0006% error which means that 5000 element is enough for this problem.

5.4 Solution of ANSYS

The reaction data of cable F1- F2c solved by ANSYS can be seen in Table 5.3.

Table 5.3 Support reactions of cable F1-F2c given by ANSYS.

F1-F2c					
Number of elements		100	500	1000	5000
Support Reactions (N)	F1	226230,43	224685,73	224448,29	224270,94
	R1	23037,47	22980,46	22920,09	22867,71
	R2	22689,94	22053,53	22058,93	22021,56
	R3	20718,40	20975,65	20870,25	20878,30
	R4	19763,40	19510,54	19548,75	19527,77
	R5	18350,37	18049,64	18042,16	18059,45
	R6	16624,45	16686,45	16648,23	16591,25
	F2c	223536,87	221968,07	221744,43	221583,08

The convergence of the solution for different number of elements is shown in Figure 5.2.

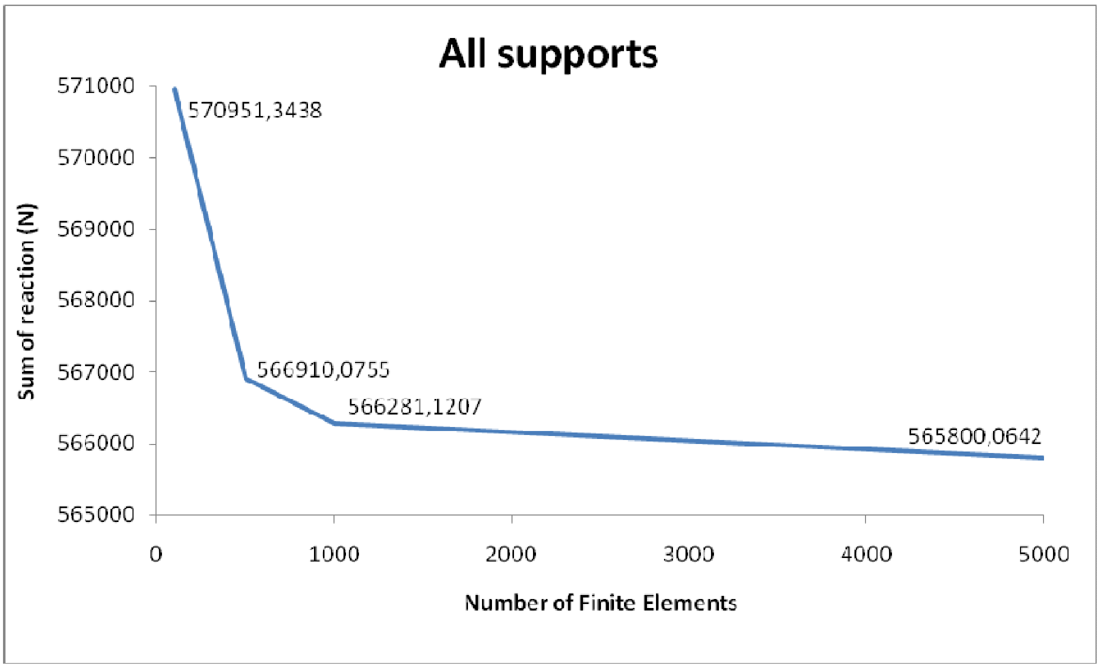

Figure 5.2 Sum of support reactions for cable F1-F2c given by ANSYS.

There is 481N difference between 1000 and 5000 element solution. This corresponds to 0.085% error.

5.5 Comparison

Comparison is made in the same way as in chapter 4. Maximum number of element, which is 5000, is used for solution of both programs. Reactions at supports are compared for all configurations.

Reaction results of each three configuration having 5000 elements are sorted in Table 5.4, Table 5.5 and Table 5.6.

Table 5.4 Support reactions for cable F1-F2a.

F1-F2a			
Solution types		CABPOS	ANSYS
Support reactions (N)	F1	2861,03	2859,14
	R1	1239,51	1240,29
	R2	1212,78	1212,07
	R3	1177,38	1177,65
	R4	1139,48	1139,42
	R5	1118,15	1118,53
	R6	596,13	596,49
	F2a	831,34	831,01

Table 5.5 Support reactions for cable F1-F2b.

F1-F2b			
Solution types		CABPOS	ANSYS
Support reactions (N)	F1	4621,47	4618,39
	R1	1408,52	1408,76
	R2	1374,28	1374,32
	R3	1327,64	1327,74
	R4	1273,07	1272,53
	R5	1215,29	1215,65
	R6	977,02	977,30
	F2b	2011,53	2008,40

Table 5.6 Support reactions for cable F1-F2c.

F1-F2c			
Solution types		CABPOS	ANSYS
Support reactions (N)	F1	224219,97	224270,94
	R1	22856,15	22867,71
	R2	22017,52	22021,56
	R3	20870,82	20878,30
	R4	19518,80	19527,77
	R5	18061,12	18059,45
	R6	16581,27	16591,25
	F2c	221521,81	221583,08

Related percentages of errors are tabulated below in Table 5.7.

Table 5.7 Error of percentages for single-segment cable solution.

Error of percentages			
Supports	Cable configurations		
	F1-F2a	F1-F2b	F1-F2c
F1	0,0664%	0,0666%	0,0227%
R1	0,0633%	0,0165%	0,0505%
R2	0,0586%	0,0029%	0,0183%
R3	0,0232%	0,0078%	0,0358%
R4	0,0067%	0,0429%	0,0459%
R5	0,0340%	0,0301%	0,0092%
R6	0,0611%	0,0291%	0,0602%
F2	0,0402%	0,1555%	0,0277%

ANSYS and CABPOS give approximately same results for all cable configurations. Average errors for F1-F2a, F1-F2b and F1-F2c configurations are 0.0442%, 0.0439% and 0.0338% respectively. These amounts of errors are admissible for a structural member.

Profile of cables F1-F2a, F1-F2b and F1-F2c are shown in **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.** respectively.

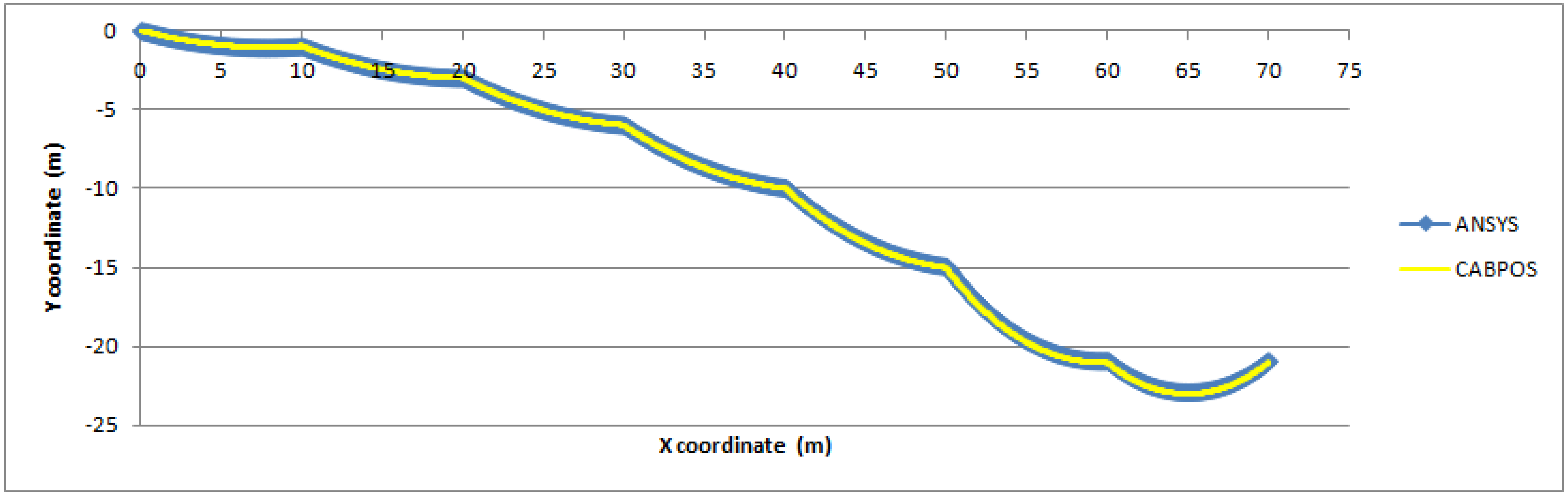

Figure 5.3 Profile of cable F1-F2a

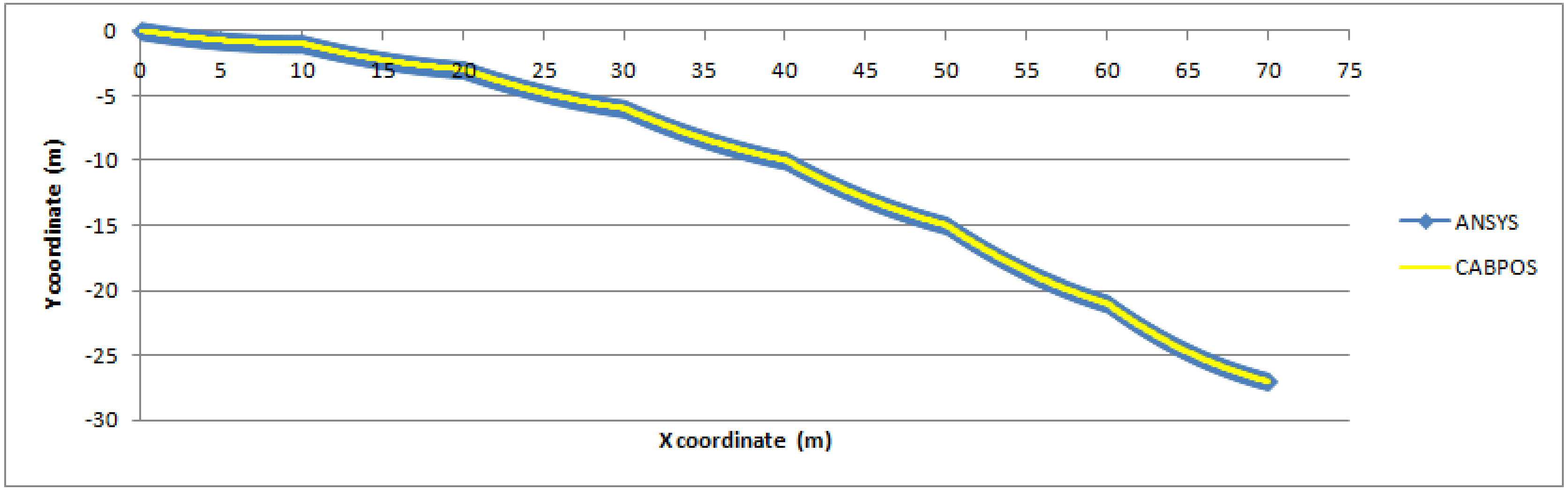

Figure 5.4 Profile of cable F1-F2b

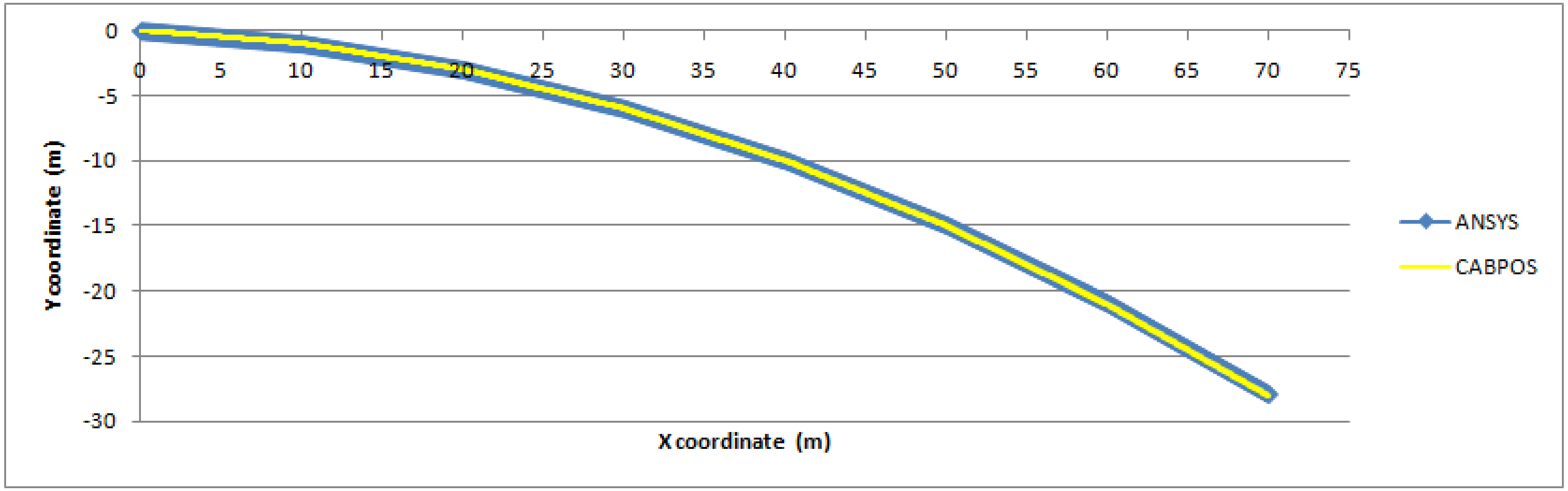

Figure 5.5 Profile of cable F1-F2c

CHAPTER 6

COMPUTER PROGRAM: CABPOS (CABLE POSITIONING)

6.1 General

CABPOS is a program which is build for the purpose of analyzing and positioning of cables having different support conditions. Lots of routines have been written by programmers in the past. Those programs analyze only the single-segment cable problems having 2 fixed supports at the ends of the cable. CABPOS is a further program for cable analysis. It analysis not only the single-segment cables but also the multi-segment continuous cables. Multi-segment continuous cable is a cable which is supported by two fixed support at both ends, in addition, it is supported by roller supports between the ends.

FORTRAN programming language is used for building CABPOS. It is based on a main program which runs many subroutines. Main program and subroutines will be introduced later. Before these, main procedure will be defined. Code of CABPOS is given on Appendix A.

6.2 Procedure

Basically, program has three input and five output text files. Program gets the cable properties, environment conditions, coordinates of supports and data for modulus of elasticity from input and gives the nodal coordinates of cable, support reactions, final coordinates of roller supports, lengths for each segment and end forces of cable for each segment. In those input text files data should be written in consistent units.

Solution is found by two methods. These are direct stiffness method and tension distribution method. Direct stiffness method is used for tight cable and tension distribution method is used for slack cable problems. Although tension distribution method solves both problems, it takes lots of time for solution. Besides, direct stiffness method could not solve slack cable problems, because of a property of cable explained before.

Principle of direct stiffness method is basis on changing length of each segment. Change in reaction difference of cable on each support is found by changing length of each segment. Stiffness matrix is formed by the data of change in reaction difference of cable on each support. The increment of length for each segment is found form stiffness matrix analysis. This procedure is made several iterations of Newton-Raphson method, because of nonlinear behavior of cable.

Principle of tension distribution method is same as direct stiffness method. Stiffness method makes a total calculation on the other hand; tension distribution method makes calculations between two successive segments. It founds the increment of length for successive segments by changing the length of cables connected on a roller support. This calculation is made for each roller support.

6.3 Main Program

The main program of CABPOS get the input data from the text file and checks whether the system is a single-segment cable problem or multi-segment continuous cable problem. Accordingly it leads. Then it checks whether the cable is tight or slack. After that classification of the problem, program runs the subroutines MSPFTC and MSPFSC respectively.

Operation of checker for tightness basis on a simple principle; It firstly, calculate the total direct length of the path, which cable should keep, by the subroutine COTLOES. Secondly, it checks whether total cable length is greater than 1.1 times of total direct length of the path. The number 1.1 is an experimental constant made on this computer program.

MSPFTC is a subroutine for direct stiffness method MSPFSC is a subroutine for tension distribution method. After the solution of main subroutines MSPFTC and MSPFSC, program gives the output.

Subroutines used in main program are:

- MSPFTC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC,R)
- MSPFSC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC,R)
- INPUT1(TCL,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN)
- INPUT2(NOS,SX,SY,SZ)
- COTLOES(NOS,SX,SY,SZ,TLOES,TTLOC)
- COSCLOES(NOS,TLOES,TTLOC,TCL,LOES)
- DOS(NOS,SY,TLOES,TCL,TTLOC,LOES)
- ALAI(NOS,IOLFT,IIOL,LOES)
- AIOES(l,NOS,IIOL,LOES)
- AIOESS(k,l,NOS,IIOL,LOES)
- ACOFPFES(k,NOS,CC,C1,C2)
- COOS(k,l,NOS,X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEN,X,Y,Z,FLOC,R,IR)
- GIFTFP(X1,X2,Z1,Z2,SR)
- ACOFP(X1,Y1,Z1,IX,IY,IZ)
- ARAIOFP(SR,IIOR,IRX,IRY,IRZ,IR)
- FEC(i,WOC,FEN,FEL,MOE,AOC,TEC,TC,IR,IRX,IRY,IRZ,IX,IY,IZ,IFLOC)
- FMEC(FEN,IX,IY,IZ,IXX,IXY,IXZ,IYX,IYY,IYZ,IZX,IZY,IZZ,X2,Y2,Z2,FM,DTT)

- FRM(l,k,NOS,FEN,IR,R1,RLP)
- FRMS(l,k,NOS,FEN,IR,R1,RLP)
- TIB(l,NOS,IIOL,LOES)
- TIBS(l,k,NOS,IIOL,LOES)
- SMS(NOS,R1,RLP,DR,DDR)
- MATINV(NSTRE,AMATX)
- MATMULT(NSTRE,MATX1,MATX2,MATX3)
- OUTPUT1(NOS,FEN,X,Y,Z,FLOC,R)
- ICAAI(i,NOS,IIOL,R1,RLP,LOES)
- SOD(l,k,i,NOS,FEN,IX,IY,IZ,IR,IFLOC,X,Y,Z,R,FLOC)
- MODULUS(STRESS,STRAIN)
- OUTPUT2(NOS,FEN,X,Y,Z,FLOC,R)

6.4 Subroutines

Some of the subroutines, which are important, are introduced. The functions of those subroutines are explained. Some important variables are given by their definitions.

6.4.1 MSPFTC

MSPFTC is a subroutine which gives solution for tight cable problems. Program inputs are initial length of cable of each segment, material and coordinate properties of cable. Outputs are nodal coordinates of cable, final length of cable of each segment and nodal reactions of cable. Program runs using nested three loops. First one is iteration loop, second one is incrementation loop and the last one is segment loop.

Under the control of iteration loop stiffness matrix calculations are made by subroutines SMS, MATINV and MATMULT. After matrix calculations, check for the reaction differences between successive segments is made. If check fails, new lengths will be assigned by subroutine ALAI.

Assigning increment and taking them back is made by subroutines AIOES and TIB in incrementation loop.

In the segment loop, firstly, coordinates of first and last point of each segment are assigned by subroutine ACOFPFES. Secondly it runs the subroutine COOS which makes one segment calculation. Finally, first and last nodal reactions are formed.

Variable	Definition
R1	Reaction of first point of each segment.
RLP	Reaction of last point of each segment.
DR	Reaction difference between successive cables on each roller support for each increment.
DDR	Change in DR between nonincremented solution and incremented solution on each roller support for each iteration.
IOLFT	Solution for change in length for each segment.

6.4.2 MSPFSC

Work done by MSPFSC is same with MSPFTC, however, procedures are different. MSPFSC is a subroutine which gives solution for slack cable problems. Program inputs are initial length of cable of each segment, material and coordinate propeties of cable. Output is nodal coordinates of cable, final length of cable of each segment and nodal reactions of cable. Program runs using nested three loops. First one is iteration loop, second one is roller support loop and the last one is successive segments' loop.

Iteration loop only checks whether the reaction difference between successive segment cables are greater than precision needed. If check fails, iteration will goes on.

Change in length between two successive supports is calculated and length of each segment is renewed in Roller support loop.

The last loop is successive segments loop which makes calculations for analysis of successive segments connected by a roller support. This loop has two steps. In the first step, it analyzes two successive supports by nonincremented cable lengths. In the second step, same calculations are made for incremented cable lengths.

Variable	Definition
R1	Reaction of first point of each segment.
RLP	Reaction of last point of each segment.
INCR	Solution for change in length for each segment.

6.4.3 INPUT1

INPUT1 gathers the information from the text file about cable properties. Those cable properties and their variable names in program code are as follows.

Variable	Definition
NOS	Number of segment.
FEN	Finite element number.
TCL	Total cable length.
DOC	Diameter of cable.
WOC	Weight of cable per length.
MOE	Modulus of elasticity.
PLP	Precision for second support coordinates.
TEC	Thermal expansion coefficient.
TC	Temperature change.

6.4.4 INPUT2

This subroutine gathers the coordinates of two fixed supports and roller supports. Fixed supports should be written in first row and last row in the text file. The data between those fixed support data are coordinates of roller supports. Additionally, cable will be positioned in the order of supports written in the text file.

6.4.5 COTLOES

This subroutine calculates the direct length of the path of the cable. It gives total direct length of the cable path and direct length of each segments' cable path.

Variable	Definition
TLOES	Direct length of each segments' cable path.
TTLOC	Total direct length of cable path.

6.4.6 COSCLOES

Initial cable lengths must be given for solution. COSCLOES calculates the initial cable lengths for each segment to start the calculation. Total cable length is distributed to each segment proportional to their direct length of cable path.

Variable	Definition
LOES	Length of cable of each segment.

6.4.7 DOS

Most of the sag of the cable would be occur on the segment having less elevation. In other words, cable will slip on the roller supports to the lower elevations.

This subroutine gives whole sag of the cable to the segment which has the less elevation. It renews the initial length of cable of each segment. The aim of this renew is to decrease the iteration number of the program.

Variable	Definition
MINCOOR	Index for segment having minimum elevation. This elevation is calculated by the sum of y coordinates of two supports of a segment.

6.4.8 ALAI

This subroutine adds the calculated increment to the cable length of each segment.

6.4.9 AIOES

This subroutine gives the imaginary increment in length of each segment.

6.4.10 COOS

COOS is the main subroutine of the program. It makes the calculations of one segment. Inputs are coordinates of supports of one segment and material properties of cable. Outputs are nodal coordinates, final cable length after deformation and nodal reactions. COOS runs with two nested loop. First one is iteration loop, second one is finite element loop.

As previously introduced in chapter 2, initial reaction of first node of cable is given by GIFTFP to make the system determinant. Imaginary increment is applied to this reaction in all three directions in incrementation loop. Flexibility matrix is formed by FMEC by data calculated by finite element loop. Increment for each direction is calculated and added to the initial reaction by flexibility matrix calculations. Finally, check is made for last node's coordinate whether it is approximately close to the second support of the segment.

After incrementation made in incrementation loop finite element loop processes and gives the nodal coordinates and reactions, and also final node's coordinates. This process is made four times. First one is for nonincremented reaction solution and the other three is for incremented reaction solution for three global directions.

Variable	Definition
FEL	Finite element length: This length will change segment to segment. However FEN is constant for each segment.
SR	Initial reaction of first node of each segment which is renewed after each iteration.
DRR	Increment of reaction for each direction calculated by flexibility matrix.

6.4.11 GIFTFP

Giving initial reactions for segment calculations is made by this subroutine. An approximate initial reaction decreases the iteration number of program. However, it is very hard to predict the initial reaction of cable approximately. So, GIFTFP gives a small reaction according to its orientation. In other words, this subroutine only determines the direction of the reaction and assigns it.

6.4.12 FEC

Finite element calculations are made by FEC. Nodal coordinates and reactions are calculated in this subroutine.

Variable	Definition
STRAIN	Strain of a finite element.
DELTA	Elongation of a finite element.

6.4.13 FMEC

This subroutine forms the flexibility matrix of one segment. It uses coordinates of final node. This coordinates are for incremented and nonicremented reactions.

Variable	Definition
IX, IY, IZ	Coordinates of final node for nonicremented reaction case.
IXX, IXY, IXZ	Coordinates of final node for incremented reaction of X direction.

IYX, IYY, IYZ	Coordinates of final node for incremented reaction of Y direction.
IZX, IZY, IZZ	Coordinates of final node for incremented reaction of Z direction.
SOL	Approximation for final node of the segment.

6.4.14 MATINV

Matrix inversion is made by MATINV. The given square matrix is renewed by the inverse of it.

Variable	Definition
NSTRE	Dimension of matrix.
AMATX	Matrix to be inverted.

6.4.15 MATMULT

Multiplication of a square matrix FM1, having dimension NOS1, by vector SOL1 having same dimension gives vector DRR1.

6.4.16 OUTPUT1

OUTPUT1 gives the information about final cable position and forces. Those outputs are as follows.

Variable	Definition
NOS	Number of segment.
FEN	Finite element number.
X,Y,Z	Coordinates of each finite element.
FLOC	Final length of cable.
R	Reaction of each finite element.

6.4.17 MODULUS

This subroutine gets the stress strain data of cable from INPUT3 text file. Then find the strain value for corresponding stress value for each finite element by interpolation.

<u>Variable</u>	<u>Definition</u>
STRESS	Stress data.
STRAIN	Strain data.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

Cables are highly nonlinear structural members under transverse loading. This nonlinearity is mainly due to the close relationship between the final geometry under transverse loads and the resulting stresses in its equilibrium state rather than the material properties. In practice, the cables are usually used as isolated single-segment elements fixed at the ends. Various studies and solution procedures suggested by researchers are available in the literature for such isolated cables. However, not much work is available for continuous cables with multiple supports.

In this study, a multi-segment continuous cable is defined as a cable fixed at the ends and supported by a number of stationary roller supports in between. Total cable length is assumed constant and the intermediate supports are assumed to be frictionless. Therefore, the critical issue is to find the distribution of the cable length among its segments in the final equilibrium state. Since the solution of single-segment cables is available the additional condition to be satisfied for multi-segment continuous cables with multiple supports is to have stress continuity at intermediate support locations where successive cable segments meat. A predictive/corrective iteration procedure is proposed for this purpose. The solution starts with an initially assumed distribution of total cable length among the segments and each segment is analyzed as an independent isolated single-segment cable. In general, the stress continuity between the cable segments will not be satisfied unless the assumed distribution of cable length is the correct distribution corresponding to final equilibrium state. In the subsequent iterations the segment lengths are readjusted to eliminate the unbalanced tensions at segment junctions. The iterations are continued until the stress continuity is satisfied at all junctions. Two alternative approaches are proposed for the segment length adjustments: Direct stiffness method and tension distribution method.

A computer program called CABPOS is developed for the analysis of multi-segment continuous cables and both techniques have been implemented into it. The program is coded in FORTRAN. The total length of the cable, material properties, the load and environmental data, support locations and the desired density for the finite element mesh is supplied to the program by the user. The program then generates the geometry of cable segments, internal stresses and the support reactions in the final equilibrium state. A brief description of the program CABPOS is given in chapter 6.

Verification of the solutions generated by CABPOS is made by comparing the results with ANSYS. The results are satisfactory and compares well with those obtained by the commercial finite element program ANSYS. .In the ANSYS solution, the roller supports are defined as dimensionless and they are modeled as contact elements. The friction is eliminated for the contact elements by setting the tangent stiffness of the contact to zero.

7.2 Conclusions

Based on the research carried out in this study and the experienced gained from the analysis of various verification examples, the conclusions drawn can be summarized as follows:

- A solution procedure is devised for the analysis of multi-segment continuous cables with multiple supports. In general, a predictive/corrective iterative algorithm coupled with Newton-Raphson iterations is employed for the nonlinear analysis. The proposed algorithm is tested with a number of verification examples and satisfactory results are obtained.

- The behavior of slack cables is characteristically different from that of tight cables because of the order-of-magnitude difference between the cable stiffnesses in each case. Therefore, there is a need for a specific treatment for each case. Two alternative techniques are proposed for this purpose: Direct Stiffness method and Tension/Length Distribution method. The former is best suited for tight cables whereas the latter is more appropriate for slack cables. The Tension/Length Distribution approach even becomes the only choice as the degree of slackness of the cable or any segment of it increases.

- The use of Tension/Length Distribution approach unnecessarily increases the correction iterations and the use of the Direct Stiffness method causes some wild oscillations or even divergence before reaching the equilibrium state. Therefore, a proper combination of the two techniques is necessary for a general solution algorithm. For this purpose, a smart algorithm for the detection of excessive slackness in a given configuration of a cable is critical.

7.3 Recommendations for future studies

Although verification is made and results show that solutions are almost correct. Some assumptions and simplifications are made to reach the solution. Those are:

- Modulus of elasticity of the cable is assumed constant for verification. Although there is an input text files for modulus of elasticity data. There must be experimental data of a cable to use this property of CABPOS.

- Friction of the cable on roller supports is assumed zero. Thus equality of cable tensions on each roller support is enough for static equilibrium.

- Flexural rigidity of cable is assumed zero. Because, the cables used in structural systems are long enough to neglect flexural rigidity.

- 1.1 times the span of multi-segment continuous cable is used as a limit for classification of system as very slack cable.

- There are some assumptions due to finite element modeling like similars have.

Therefore, some recommendations are given for further research;

- CABPOS has tool for variable modulus of elasticity. This tool could be run by using stress-strain data of a cable and verification could be made by a computer program.
- Some friction could be applied on roller supports and also verification could be made with a computer program.
- Flexural and shear rigidities can be considered in analysis. Although it does not affect large scale systems, there would be effect on small scale cable systems.
- Verification of the proposed methods can be made experimentally.
- Although there is a research about the degree of slackness of a single-segment cable in this thesis, this study is superficial. Therefore, a parametric study about the degree of slackness can be carried out.
- An empirical value of 1.1 is determined by experiences obtained through the solution of sample problems. This number can be revised by some well settled studies or another way to determine the degree of slackness of multi-segment cable can be found.

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APPENDIX A

CODE OF CABPOS

```
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT LENGTH
!TCL : TOTAL CABLE LENGTH
!DOC : DIAMETER OF CABLE
!WOC : WEIGTH OF CABLE
!MOE : MODULUS OF ELASTICITY
!TEC : THERMAL EXPANSION COEFFICIENT
!TC : THERMAL CHANGE
!PLP : PRECISION OF LAST POINT
!SX,SY,SZ : COORDINATES OF EACH SUPPORT
!X,Y,Z : COORDINATES OF EACH SEGMENT AND EACH FINITE ELEMENT
!FLOC : FINAL LENGTH OF CABLE OF EACH SEGMENT
!R : REACTION OF EACH SEGMENT AND EACH FINITE ELEMENT
!IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH SEGMENT
!TTLOC : TOTAL TRAPEZOIDAL LENGTH OF CABLE
!TLOES : TRAPEZOIDAL LENGTH OF EACH SEGMENT
!LOES : LENGTH OF EACH SEGMENT
INTEGER NOS,FEN
DOUBLE PRECISION TCL,DOC,WOC,MOE,TEC,TC,PLP
DOUBLE PRECISION SX(100),SY(100),SZ(100)
DOUBLE PRECISION
X(100,10000),Y(100,10000),Z(100,10000),FLOC(100),R(100,10000),IR(10000)
```

```
DOUBLE PRECISION TTLOC,TLOES(100),LOES(100)

!INPUT1 DATA

CALL INPUT1(TCL,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN)

!INPUT2 DATA

CALL INPUT2(NOS,SX,SY,SZ)

!CHECK FOR SINGLE SEGMENT

IF (NOS.NE.1) GOTO 63

  CALL
COOS(1,1,NOS,SX(1),SY(1),SZ(1),SX(2),SY(2),SZ(2),TCL,DOC,WOC,MOE,TEC
,TC,PLP,FEN,X,Y,Z,FLOC,R,IR)

  CALL OUTPUT1(NOS,FEN,X,Y,Z,FLOC,R)

  GOTO 64

63 CONTINUE

!CALCULATION OF TRAPEZOIDAL LENGTH OF EACH SEGMENT

TTLOC=0

CALL COTLOES(NOS,SX,SY,SZ,TLOES,TTLOC)

!CALCULATION OF STARTING CABLE LENGTH OF EACH SEGMENT

CALL COSCLOES(NOS,TLOES,TTLOC,TCL,LOES)

!CHECK FOR TIGHT OR SAG CABLE

IF(TCL.GT.TTLOC*1.1)GOTO 52

!MULTISEGMENT PROGRAM FOR TIGHT CABLE

CALL
MSPFTC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC
,R)

GOTO 53

52 CONTINUE

!DETERMINATION OF SAG

CALL DOS(NOS,SY,TLOES,TCL,TTLOC,LOES)

!MULTISEGMENT PROGRAM FOR SAG CABLE
```

```
CALL
MSPFSC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC
,R)

53 CONTINUE

!OUTPUT1 DATA

CALL OUTPUT1(NOS,FEN,X,Y,Z,FLOC,R)

CALL OUTPUT2(NOS,FEN,X,Y,Z,FLOC,R)

64 CONTINUE

END


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR MULTISEGMENT PROGRAM FOR TIGHT CABLE

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!NOS : NUMBER OF SEGMENT

!FEN : FINITE ELEMENT LENGTH

!X1,Y1,Z1 : FIRST COORDINATE OF SEGMENT

!X2,Y2,Z2 : SECOND COORDINATE OF SEGMENT

!CL : CABLE LENGTH OF SEGMENT

!DOC : DIAMETER OF CABLE

!WOC : WEIGTH OF CABLE

!MOE : MODULUS OF ELASTICITY

!TEC : THERMAL EXPANSION COEFFICIENT

!TC : THERMAL CHANGE

!PLP : PRECISION OF LAST POINT

!SX,SY,SZ : SUPPORT COORDINATES

!LOES : LENGTH OF EACH SEGMENT

!IIOL : IMAGINARY INCREMENTATION ON LENGTH

!IOLFT : INCREMENTATION OF LENGTH

!X,Y,Z : COORDINATES OF EACH SEGMENT AND EACH FINITE ELEMENT
```

```
!R : REACTION OF EACH SEGMENT AND EACH FINITE ELEMENT

!FLOC : FINAL LENGTH OF CABLE OF EACH SEGMENT

!IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH SEGMENT

!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION

!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION

!DR : REACTION DIFFERENCE ON EACH SUPPORT

!DDR : CHANGE IN REACTION DIFFERENCE ON EACH SUPPORT FOR
EACH INCREMENTATION

SUBROUTINE
MSPFTC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC
,R)

INTEGER NOS,FEN

DOUBLE PRECISION X1,Y1,X2,Y2,Z1,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP

DOUBLE PRECISION SX(NOS+1),SY(NOS+1),SZ(NOS+1),LOES(NOS)

DOUBLE PRECISION IIOL,IOLFT(NOS-1,1)

DOUBLE PRECISION
X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1),R(NOS,FEN+1),FLOC(NOS)

DOUBLE PRECISION IR(FEN+1),R1(NOS,NOS),RLP(NOS,NOS)

DOUBLE PRECISION DR(NOS-1,NOS),DDR(NOS-1,NOS-1)

IIOL=0.000001

DO 48 i=1,(NOS-1)

  IOLFT(i,1)=0

48 CONTINUE

!ITERATION LOOP

DO 19 m=1,100

  !ASSIGNING LENGTH AND INCREMENTATION

  CALL ALAI(NOS,IOLFT,IIOL,LOES)

  !INCREMENTATION LOOP

  DO 20 l=1,NOS

    !ASSIGNING INCREMENTATION ON EACH SUPPORT
```

```
  CALL AIOES(l,NOS,IIOL,LOES)
  !SEGMENT LOOP
  DO 22 k=1,NOS
   !ASSIGNING COORDINATES OF FIRST POINT FOR EACH SEGMENT
   CALL ACOFPFES(k,NOS,SX,X1,X2)
   CALL ACOFPFES(k,NOS,SY,Y1,Y2)
   CALL ACOFPFES(k,NOS,SZ,Z1,Z2)
   !CALCULATION OF ONE SEGMENT
   CL=LOES(k)
   CALL
COOS(k,l,NOS,X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEN,X,Y,
Z,FLOC,R,IR)

   !FORMING REACTION MATRICE
   CALL FRM(l,k,NOS,FEN,IR,R1,RLP)
  22 CONTINUE
  !TAKING INCREMENTATION BACK
  CALL TIB(l,NOS,IIOL,LOES)
 20 CONTINUE
 !FORMING STIFFNESS MATRICE
 CALL SMS(NOS,R1,RLP,DR,DDR)
 !STIFFNESS MATRICE INVERSION
 CALL MATINV((NOS-1),DDR)
 !MATRICE MULTIPLICATION
 CALL MATMULT((NOS-1),DDR,DR,IOLFT)
 !CHECK FOR REACTION PRECISION
 DO 47 n=1,(NOS-1)
  IF((RLP(1,n)-RLP(1,n)*PLP).LT.R1(1,n+1)) GOTO 30
  GOTO 19
```

```
  30 IF((RLP(1,n)+RLP(1,n)*PLP).GT.R1(1,n+1)) GOTO 47
  GOTO 19
 47 CONTINUE
 GOTO 33
19 CONTINUE
33 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR MULTISEGMENT PROGRAM FOR SAG CABLE
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT LENGTH
!X1,Y1,Z1 : FIRST COORDINATE OF SEGMENT
!X2,Y2,Z2 : SECOND COORDINATE OF SEGMENT
!CL : CABLE LENGTH OF SEGMENT
!DOC : DIAMETER OF CABLE
!WOC : WEIGTH OF CABLE
!MOE : MODULUS OF ELASTICITY
!TEC : THERMAL EXPANSION COEFFICIENT
!TC : THERMAL CHANGE
!PLP : PRECISION OF LAST POINT
!SX,SY,SZ : SUPPORT COORDINATES
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LENGTH OF EACH SEGMENT
!X,Y,Z : COORDINATES OF EACH SEGMENT AND EACH FINITE ELEMENT
!R : REACTION OF EACH SEGMENT AND EACH FINITE ELEMENT
!FLOC : FINAL LENGTH OF CABLE OF EACH SEGMENT
!IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH SEGMENT
```

```
!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION

!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION

SUBROUTINE
MSPFSC(LOES,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN,SX,SY,SZ,X,Y,Z,FLOC
,R)

INTEGER NOS,FEN

DOUBLE PRECISION X1,Y1,X2,Y2,Z1,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP

DOUBLE PRECISION SX(NOS+1),SY(NOS+1),SZ(NOS+1)

DOUBLE PRECISION IIOL,LOES(NOS)

DOUBLE PRECISION
X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1),R(NOS,FEN+1),FLOC(NOS)

DOUBLE PRECISION IR(FEN+1),R1(NOS,2),RLP(NOS,2)

IIOL=0.000001

!ITERATION LOOP

DO 100 m=1,1000

  !SEGMENT LOOP

  DO 101 k=1,(NOS-1)

    !INCREMENTATION LOOP

    DO 102 l=1,2

      !ASSIGNING INCREMENTATION ON EACH SUPPORT

      CALL AIOESS(k,l,NOS,IIOL,LOES)

      !ASSIGNING COORDINATES OF FIRST POINT FOR EACH SEGMENT

      CALL ACOFPFES(k,NOS,SX,X1,X2)

      CALL ACOFPFES(k,NOS,SY,Y1,Y2)

      CALL ACOFPFES(k,NOS,SZ,Z1,Z2)

      !CALCULATION OF ONE SEGMENT

      CL=LOES(k)

      CALL
COOS(k,l,NOS,X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEN,X,Y,
Z,FLOC,R,IR)
```

```
!FORMING REACTION MATRICE
CALL FRMS(k,l,NOS,FEN,IR,R1,RLP)
!ASSIGNING COORDINATES OF FIRST POINT FOR EACH SEGMENT
CALL ACOFPFES(k+1,NOS,SX,X1,X2)
CALL ACOFPFES(k+1,NOS,SY,Y1,Y2)
CALL ACOFPFES(k+1,NOS,SZ,Z1,Z2)
!CALCULATION OF ONE SEGMENT
CL=LOES(k+1)
CALL
COOS(k+1,l,NOS,X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEN,X,
Y,Z,FLOC,R,IR)
!FORMING REACTION MATRICE
CALL FRMS(k+1,l,NOS,FEN,IR,R1,RLP)
!TAKING INCREMENTATION BACK
CALL TIBS(k,l,NOS,IIOL,LOES)
102 CONTINUE
!INCREMENTATION CALCULATION AND APPLYING
INCREMENTATION
CALL ICAAI(k,NOS,IIOL,R1,RLP,LOES)
101 CONTINUE
!CHECK FOR REACTION PRECISION
DO 103 n=1,(NOS-1)
IF((RLP(n,1)-RLP(n,1)*PLP).LT.R1(n+1,1)) GOTO 104
GOTO 100
104 IF((RLP(n,1)+RLP(n,1)*PLP).GT.R1(n+1,1)) GOTO 103
GOTO 100
103 CONTINUE
GOTO 105
100 CONTINUE
105 CONTINUE
```

```
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR INPUT1 DATA
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT NUMBER
!NAME : NAME (EXPLANATION) OF DATA
!TCL : TOTAL CABLE LENGTH
!DOC : DIAMETER OF CABLE
!WOC : WEIGTH OF CABLE
!MOE : MODULUS OF ELASTICITY
!PLP : PRECISION OF LAST POINT
!TEC : THERMAL EXPANSION COEFFICIENT
!TC : THERMAL CHANGE
SUBROUTINE INPUT1(TCL,NOS,DOC,WOC,MOE,TEC,TC,PLP,FEN)
INTEGER NOS,FEN
CHARACTER*30 NAME(9)
DOUBLE PRECISION TCL,DOC,WOC,MOE,PLP,TEC,TC
OPEN(10,file='INPUT1.txt')
  READ(10,11)NAME(1),TCL
  READ(10,12)NAME(2),NOS
  READ(10,11)NAME(3),DOC
  READ(10,11)NAME(4),WOC
  READ(10,11)NAME(5),MOE
  READ(10,11)NAME(6),TEC
  READ(10,11)NAME(7),TC
  READ(10,11)NAME(8),PLP
  READ(10,12)NAME(9),FEN
```

```
11 FORMAT(A30,F20.10)
12 FORMAT(A30,I20.10)
CLOSE(10)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR INPUT2 DATA
!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!SX : X COORDINATE OF SUPPORTS
!SY : Y COORDINATE OF SUPPORTS
!SZ : Z COORDINATE OF SUPPORTS
SUBROUTINE INPUT2(NOS,SX,SY,SZ)
INTEGER NOS
DOUBLE PRECISION SX(NOS+1),SY(NOS+1),SZ(NOS+1)
OPEN(13,file='INPUT2.txt')
DO 14 i=1,(NOS+1)
  READ(13,16)SX(i),SY(i),SZ(i)
  16 FORMAT(3F20.10)
14 CONTINUE
CLOSE(13)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR CALCULATION OF TRAPEZOIDAL LENGTH OF EACH
SEGMENT
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!DX,DY,DZ : DISTANCE BETWEEN COORDINATES OF SUPPORTS OF ONE
SEGMENT
!SX : X COORDINATE OF SUPPORTS
```

```
!SY : Y COORDINATE OF SUPPORTS

!SZ : Z COORDINATE OF SUPPORTS

!TLOES : TRAPEZOIDAL LENGTH OF EACH SEGMENT

!TTLOC : TOTAL TRAPEZOIDAL LENGTH OF CABLE

SUBROUTINE COTLOES(NOS,SX,SY,SZ,TLOES,TTLOC)

INTEGER NOS

DOUBLE PRECISION DX,DY,DZ

DOUBLE PRECISION
TLOES(NOS),SX(NOS+1),SY(NOS+1),SZ(NOS+1),TTLOC

DO 17 i=1,NOS

  DX=SX(i+1)-SX(i)

  DY=SY(i+1)-SY(i)

  DZ=SZ(i+1)-SZ(i)

  TLOES(i)=DX*DX+DY*DY+DZ*DZ

  TLOES(i)=SQRT(TLOES(i))

  TTLOC=TTLOC+TLOES(i)

17 CONTINUE

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR CALCULATION OF STARTING CABLE LENGTH OF
EACH SEGMENT

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!NOS : NUMBER OF SEGMENT

!TCL : TOTAL CABLE LENGTH

!TTLOC : TOTAL TRAPEZOIDAL LENGTH OF CABLE

!TLOES : TRAPEZOIDAL LENGTH OF EACH SEGMENT

!LOES : LENGTH OF EACH SEGMENT

SUBROUTINE COSCLOES(NOS,TLOES,TTLOC,TCL,LOES)

INTEGER NOS
```

```
DOUBLE PRECISION TCL,TTLOC,TLOES(NOS),LOES(NOS)

DO 18 i=1,NOS

  LOES(i)=TLOES(i)/TTLOC*TCL

18 CONTINUE

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR DETERMINATION OF SAG

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!NOS : NUMBER OF SEGMENT

!MINCOOR : INDEX OF SEGMENT HAVING MINIMUM CORDINATES

!SY : Y COORDINATE OF SUPPORTS

!LOES : LENGTH OF EACH SEGMENT

!TCOOR : SUM OF COORDINATES OF SUCCESSIVE ROLLER SUPPORTS Y
DIRECTION

!TLOES : TRAPEZOIDAL LENGTH OF EACH SEGMENT

!TCL : TOTAL CABLE LENGTH

!TTLOC : TOTAL TRAPEZOIDAL LENGTH OF CABLE

SUBROUTINE DOS(NOS,SY,TLOES,TCL,TTLOC,LOES)

INTEGER NOS,MINCOOR

DOUBLE PRECISION
SY(NOS+1),LOES(NOS),TCOOR(NOS),TLOES(NOS),TCL,TTLOC

DO 54 i=1,NOS

  TCOOR(i)=SY(i)+SY(i+1)

54 CONTINUE

MINCOOR=1

DO 55 i= 2,NOS

  IF(TCOOR(i).GT.TCOOR(MINCOOR)) GOTO 55

  MINCOOR=i

55 CONTINUE
```

```
DO 57 i=1,NOS
  IF (MINCOOR.EQ.i) GOTO 58
  LOES(i)=TLOES(i)
  GOTO 57
  58 LOES(i)=TCL-TTLOC+TLOES(i)
57 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR ASSIGNING LENGTH AND INCREMENTATION
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!IOLFT : INCREMENTATION ON LENGTH
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LENGTH OF EACH SEGMENT
SUBROUTINE ALAI(NOS,IOLFT,IIOL,LOES)
INTEGER NOS
DOUBLE PRECISION IOLFT(NOS-1,1),IIOL,LOES(NOS)
LOES(1)=LOES(1)+IOLFT(1,1)*IIOL
DO 42 i=2,(NOS-1)
  LOES(i)=LOES(i)-IOLFT(i-1,1)*IIOL+IOLFT(i,1)*IIOL
42 CONTINUE
LOES(NOS)=LOES(NOS)-IOLFT(NOS-1,1)*IIOL
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR ASSIGNING INCREMENTATION ON EACH SUPPORT
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!l : INCREMENTATION LOOP
!NOS : NUMBER OF SEGMENT
```

```
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LENGTH OF EACH SEGMENT
SUBROUTINE AIOES(l,NOS,IIOL,LOES)
INTEGER l,NOS
DOUBLE PRECISION IIOL,LOES(NOS)
IF (l.EQ.1) GOTO 21
LOES(l-1)=LOES(l-1)-IIOL
LOES(l)=LOES(l)+IIOL
21 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR ASSIGNING INCREMENTATION ON EACH SUPPORT
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!k : SEGMENT LOOP
!l : INCREMENTATION LOOP
!NOS : NUMBER OF SEGMENT
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LENGTH OF EACH SEGMENT
SUBROUTINE AIOESS(k,l,NOS,IIOL,LOES)
INTEGER k,l,NOS
DOUBLE PRECISION IIOL,LOES(NOS)
IF (l.EQ.1) GOTO 21
LOES(k)=LOES(k)-IIOL
LOES(k+1)=LOES(k+1)+IIOL
21 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR ASSIGNING COORDINATES OF FIRST POINT FOR
EACH SEGMENT
```

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!k : SEGMENT LOOP
!NOS : NUMBER OF SEGMENT
!CC : SUPPORT COORDINATES
!C1 : FIRST SUPPORT COORDINATE OF EACH SEGMENT
!C2 : SECOND SUPPORT COORDINATE OF EACH SEGMENT
SUBROUTINE ACOFPFES(k,NOS,CC,C1,C2)
INTEGER k,NOS
DOUBLE PRECISION CC(NOS+1),C1,C2
C1=CC(k)
C2=CC(k+1)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR CALCULATION OF ONE SEGMENT
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!FEN : FINITE ELEMENT NUMBER
!k : SEGMENT LOOP
!l : INCREMENTATION LOOP
!NOS : NUMBER OF SEGMENT
!X1,Y1,Z1 : FIRST SUPPORT COORDINATE
!X2,Y2,Z2 : SECOND SUPPORT COORDINATE
!CL : CABLE LENGTH
!DOC : DIAMETER OF CABLE
!WOC : WEIGTH OF CABLE
!MOE : MODULUS OF ELASTICITY
!TEC : THERMAL EXPANSION COEFFICIENT
!TC : THERMAL CHANGE
!PLP : PRECISION OF LAST POINT
```

!FEL : FINITE ELEMENT LEGTH

!AOC : AREA OF CABLE

!IFLOC : IMAGINARLY NONINCREMENTED FINITE ELEMENT LENGTH OF CABLE

!IXFLOC : IMAGINARLY X INCREMENTED FINITE ELEMENT LENGTH OF CABLE

!IYFLOC : IMAGINARLY Y INCREMENTED FINITE ELEMENT LENGTH OF CABLE

!IZFLOC : IMAGINARLY Z INCREMENTED FINITE ELEMENT LENGTH OF CABLE

!IRX,IRY,IRZ,IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH FINITE ELEMENT

!IXRX,IXRY,IXRZ,IXR : IMAGINARLY X INCREMENTED REACTIONS OF EACH FINITE ELEMENT

!IYRX,IYRY,IYRZ,IYR : IMAGINARLY Y INCREMENTED REACTIONS OF EACH FINITE ELEMENT

!IZRX,IZRY,IZRZ,IZR : IMAGINARLY Z INCREMENTED REACTIONS OF EACH FINITE ELEMENT

!IX,IY,IZ : IMAGINARLY NONINCREMENTED COORDINATE OF EACH FINITE ELEMENT

!IXX,IXY,IXZ : IMAGINARLY X INCREMENTED COORDINATE OF EACH FINITE ELEMENT

!IYX,IYY,IYZ : IMAGINARLY Y INCREMENTED COORDINATE OF EACH FINITE ELEMENT

!IZX,IZY,IZZ : IMAGINARLY Z INCREMENTED COORDINATE OF EACH FINITE ELEMENT

!SR : IMAGINARY FIRST REACTION OF EACH SEGMENT

!IIOR : IMAGINARY INCREMENTATION ON REACTION

!IOR : INCREMENTATION ON REACTION

!FM : FLEXIBILITY MATRIX

!DTT : DISTANCE TO THE TARGET

!X,Y,Z : COORDINATE OF EACH FINITE ELEMENT

!FLOC :FINAL LENGTH OF CABLE

```
!R : REACTION OF EACH FINITE ELEMENT

!IR : FIRST AND LAST REACTIONS OF EACH SEGMENT

SUBROUTINE
COOS(k,l,NOS,X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEN,X,Y,
Z,FLOC,R,IR)

INTEGER FEN,k,l,NOS

DOUBLE PRECISION
X1,Y1,Z1,X2,Y2,Z2,CL,DOC,WOC,MOE,TEC,TC,PLP,FEL,AOC,IFLOC,IXFLO
C,IYFLOC,IZFLOC

DOUBLE PRECISION
IRX(FEN+1),IRY(FEN+1),IRZ(FEN+1),IX(FEN+1),IY(FEN+1),IZ(FEN+1),IR(FE
N+1)

DOUBLE PRECISION
IXRX(FEN+1),IXRY(FEN+1),IXRZ(FEN+1),IXX(FEN+1),IXY(FEN+1),IXZ(FEN
+1),IXR(FEN+1)

DOUBLE PRECISION
IYRX(FEN+1),IYRY(FEN+1),IYRZ(FEN+1),IYX(FEN+1),IYY(FEN+1),IYZ(FEN
+1),IYR(FEN+1)

DOUBLE PRECISION
IZRX(FEN+1),IZRY(FEN+1),IZRZ(FEN+1),IZX(FEN+1),IZY(FEN+1),IZZ(FEN+
1),IZR(FEN+1)

DOUBLE PRECISION SR(3),IIOR(3),IOR(3),FM(3,3),DTT(3)

DOUBLE PRECISION
X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1),R(NOS,FEN+1),FLOC(NOS)

FEL=CL/FEN

AOC=3.14/4*DOC*DOC

!GIVING INITIAL FORCE TO FIRST POINT

CALL GIFTFP(X1,X2,Z1,Z2,SR)

!ASSIGNING COORDINATES OF FIRST POINT

CALL ACOFP(X1,Y1,Z1,IX,IY,IZ)

CALL ACOFP(X1,Y1,Z1,IXX,IXY,IXZ)

CALL ACOFP(X1,Y1,Z1,IYX,IYY,IYZ)

CALL ACOFP(X1,Y1,Z1,IZX,IZY,IZZ)

!LOOP FOR ITERATION
```

```
DO 13 j=1,10000
      !ASSIGNING REACTIONS AND INCREMENTATION OF FIRST POINT
  IIOR(1)=0
  IIOR(2)=0
  IIOR(3)=0
      CALL ARAIOFP(SR,IIOR,IRX,IRY,IRZ,IR)
  IIOR(1)=1
  CALL ARAIOFP(SR,IIOR,IXRX,IXRY,IXRZ,IXR)
  IIOR(1)=0
  IIOR(2)=1
  CALL ARAIOFP(SR,IIOR,IYRX,IYRY,IYRZ,IYR)
  IIOR(2)=0
  IIOR(3)=1
  CALL ARAIOFP(SR,IIOR,IZRX,IZRY,IZRZ,IZR)
  IFLOC=0
      IXFLOC=0
  IYFLOC=0
  IZFLOC=0
  !LOOP FOR FINITE ELEMENT METHOD
  DO 14 i=1,FEN
      !FINITE ELEMENT CALCULATIONONON
    CALL
FEC(i,WOC,FEN,FEL,MOE,AOC,TEC,TC,IR,IRX,IRY,IRZ,IX,IY,IZ,IFLOC)
    CALL
FEC(i,WOC,FEN,FEL,MOE,AOC,TEC,TC,IXR,IXRX,IXRY,IXRZ,IXX,IXY,IXZ,I
XFLOC)
    CALL
FEC(i,WOC,FEN,FEL,MOE,AOC,TEC,TC,IYR,IYRX,IYRY,IYRZ,IYX,IYY,IYZ,I
YFLOC)
```

```
      CALL
FEC(i,WOC,FEN,FEL,MOE,AOC,TEC,TC,IZR,IZRX,IZRY,IZRZ,IZX,IZY,IZZ,IZ
FLOC)

      !SORTING OUTPUT DATA

      CALL SOD(l,k,i,NOS,FEN,IX,IY,IZ,IR,IFLOC,X,Y,Z,R,FLOC)

   14 CONTINUE

   !FLEXIBILITY MATRIX ELEMENT CALCULATION

   CALL
FMEC(FEN,IX,IY,IZ,IXX,IXY,IXZ,IYX,IYY,IYZ,IZX,IZY,IZZ,X2,Y2,Z2,FM,DT
T)

   !FLEXIBILITY MATRIX INVERSE

   CALL MATINV(3,FM)

   !MATRIX MULTIPLICATION

   CALL MATMULT(3,FM,DTT,IOR)

   SR(1)=SR(1)+IOR(1)

   SR(2)=SR(2)+IOR(2)

   SR(3)=SR(3)+IOR(3)

   !CHECK FOR PRECISION

   IF(((X2-PLP).GT.IX(FEN+1)).OR.(IX(FEN+1).GT.(X2+PLP))) GOTO 13

         IF(((Y2-PLP).GT.IY(FEN+1)).OR.(IY(FEN+1).GT.(Y2+PLP))) GOTO 13

         IF(((Z2-PLP).GT.IZ(FEN+1)).OR.(IZ(FEN+1).GT.(Z2+PLP))) GOTO 13

   GOTO 15

13 CONTINUE

15 CONTINUE

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR GIVING INITIAL FORCE TO FIRST POINT

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!X1,Z1 : FIRST SUPPORT COORDINATES

!X2,Z2 : SECOND SUPPORT COORDINATES
```

```
!SR : IMAGINARY FIRST REACTION OF EACH SEGMENT

SUBROUTINE GIFTFP(X1,X2,Z1,Z2,SR)

DOUBLE PRECISION X1,X2,Z1,Z2,SR(3)

IF(X1.EQ.X2) SR(1)=0

IF(X1.LT.X2) SR(1)=-10

IF(X1.GT.X2) SR(1)=10

SR(2)=10

IF(Z1.EQ.Z2) SR(3)=0

IF(Z1.LT.Z2) SR(3)=-10

IF(Z1.GT.Z2) SR(3)=10

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR ASSIGNING COORDINATES OF FIRST POINT

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!X1,Y1,Z1 : FIRST COORDINATES OF EACH SEGMENT

!IX,IY,IZ : IMAGINARLY NONINCREMENTED COORDINATE OF EACH
FINITE ELEMENT

SUBROUTINE ACOFP(X1,Y1,Z1,IX,IY,IZ)

DOUBLE PRECISION X1,Y1,Z1,IX(1),IY(1),IZ(1)

IX(1)=X1

IY(1)=Y1

IZ(1)=Z1

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR ASSIGNING REACTIONS AND INCREMENTATION OF
FIRST POINT

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SR : IMAGINARY FIRST REACTION OF EACH SEGMENT

!IIOR : IMAGINARY INCREMENTATION ON FIRST REACTION
```

```
!IRX,IRY,IRZ,IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH FINITE ELEMENT

SUBROUTINE ARAIOFP(SR,IIOR,IRX,IRY,IRZ,IR)

DOUBLE PRECISION IR(1),IRX(1),IRY(1),IRZ(1),SR(3),IIOR(3)

IRX(1)=SR(1)+IIOR(1)

IRY(1)=SR(2)+IIOR(2)

IRZ(1)=SR(3)+IIOR(3)

IR(1)=sqrt(IRX(1)*IRX(1)+IRY(1)*IRY(1)+IRZ(1)*IRZ(1))

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR FLEXIBILITY MATRIX ELEMENT CALCULATION

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!FEN : FINITE ELEMENT NUMBER

!IX,IY,IZ : IMAGINARLY NONINCREMENTED COORDINATES OF EACH FINITE ELEMENT

!IXX,IXY,IXZ : IMAGINARLY X INCREMENTED COORDINATES OF EACH FINITE ELEMENT

!IYX,IYY,IYZ : IMAGINARLY Y INCREMENTED COORDINATES OF EACH FINITE ELEMENT

!IZX,IZY,IZZ : IMAGINARLY Z INCREMENTED COORDINATES OF EACH FINITE ELEMENT

!X2,Y2,Z2 : SECOND SUPPORT COORDINATE

!FM : FLEXIBILITY MATRIX

!DTT : DISTANCE TO TARGET

SUBROUTINE FMEC(FEN,IX,IY,IZ,IXX,IXY,IXZ,IYX,IYY,IYZ,IZX,IZY,IZZ,X2,Y2,Z2,FM,DTT)

INTEGER FEN

DOUBLE PRECISION IX(FEN+1),IY(FEN+1),IZ(FEN+1),X2,Y2,Z2

DOUBLE PRECISION IXX(FEN+1),IXY(FEN+1),IXZ(FEN+1)

DOUBLE PRECISION IYX(FEN+1),IYY(FEN+1),IYZ(FEN+1)
```

```
DOUBLE PRECISION IZX(FEN+1),IZY(FEN+1),IZZ(FEN+1)
DOUBLE PRECISION FM(3,3),DTT(3)
FM(1,1)=IXX(FEN+1)-IX(FEN+1)
FM(2,1)=IXY(FEN+1)-IY(FEN+1)
FM(3,1)=IXZ(FEN+1)-IZ(FEN+1)
FM(1,2)=IYX(FEN+1)-IX(FEN+1)
FM(2,2)=IYY(FEN+1)-IY(FEN+1)
FM(3,2)=IYZ(FEN+1)-IZ(FEN+1)
FM(1,3)=IZX(FEN+1)-IX(FEN+1)
FM(2,3)=IZY(FEN+1)-IY(FEN+1)
FM(3,3)=IZZ(FEN+1)-IZ(FEN+1)
DTT(1)=X2-IX(FEN+1)
DTT(2)=Y2-IY(FEN+1)
DTT(3)=Z2-IZ(FEN+1)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR FORMING REACTION MATRICE
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!l : INCREMENTATION LOOP
!k : SEGMENT LOOP
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT NUMBER
!IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH SEGMENT
!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION
!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION
SUBROUTINE FRM(l,k,NOS,FEN,IR,R1,RLP)
INTEGER l,k,FEN,NOS
DOUBLE PRECISION IR(FEN+1),R1(NOS,NOS),RLP(NOS,NOS)
```

```
R1(l,k)=IR(1)
RLP(l,k)=IR(FEN+1)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR FORMING REACTION MATRICE
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!l : INCREMENTATION LOOP
!k : SEGMENT LOOP
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT LENGTH
!IR : IMAGINARLY NONINCREMENTED REACTIONS OF EACH SEGMENT
!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION
!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION
SUBROUTINE FRMS(l,k,NOS,FEN,IR,R1,RLP)
INTEGER l,k,FEN,NOS
DOUBLE PRECISION IR(FEN+1),R1(NOS,2),RLP(NOS,2)
R1(l,k)=IR(1)
RLP(l,k)=IR(FEN+1)
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR TAKING INCREMENTATION BACK
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!l : INCREMENTATION LOOP
!NOS : NUMBER OF SEGMENT
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LEGTH OF EACH SEGMENT
SUBROUTINE TIB(l,NOS,IIOL,LOES)
INTEGER l,NOS
```

```
DOUBLE PRECISION IIOL,LOES(NOS)
IF (l.eq.1) GOTO 29
LOES(l-1)=LOES(l-1)+IIOL
LOES(l)=LOES(l)-IIOL
29 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR TAKING INCREMENTATION BACK
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!l : SEGMENT LOOP
!k : INCREMENTATION LOOP
!NOS : NUMBER OF SEGMENT
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!LOES : LEGTH OF EACH SEGMENT
SUBROUTINE TIBS(l,k,NOS,IIOL,LOES)
INTEGER l,k,NOS
DOUBLE PRECISION IIOL,LOES(NOS)
IF (k.eq.1) GOTO 29
LOES(l)=LOES(l)+IIOL
LOES(l+1)=LOES(l+1)-IIOL
29 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR FORMING STIFFNESS MATRICE
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION
!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION
```

```
!DR : REACTION DIFFERENCE ON EACH SUPPORT

!DDR : CHANGE IN REACTION DIFFERENCE ON EACH SUPPORT FOR
EACH INCREMENTATION

SUBROUTINE SMS(NOS,R1,RLP,DR,DDR)

INTEGER NOS

DOUBLE PRECISION R1(NOS,NOS),RLP(NOS,NOS)

DOUBLE PRECISION DR(NOS-1,NOS),DDR(NOS-1,NOS-1)

DO 43 i=1,(NOS-1)

 DO 44 j=1,NOS

  DR(i,j)=RLP(j,i)-R1(j,i+1)

 44 CONTINUE

43 CONTINUE

DO 45 i=1,(NOS-1)

 DO 46 j=1,(NOS-1)

  DDR(i,j)=DR(i,j+1)-DR(i,1)

 46 CONTINUE

45 CONTINUE

END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR STIFFNESS MATRICE INVERSION

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!NSTRE : DIMENSION OF MATRIX

!AMATX : MATRIX TO BE INVERTED

SUBROUTINE MATINV(NSTRE,AMATX)

INTEGER NSTRE

DOUBLE PRECISION AMATX(NSTRE,NSTRE)

DO 23 I=1,NSTRE

 FACTR = 1.D0/AMATX(I,I)

 DO 24 J=1,NSTRE
```

```
    AMATX(I,J) = -FACTR*AMATX(I,J)
  24 CONTINUE
  DO 25 K=1,NSTRE
    IF(I.EQ.K) GOTO 25
    DO 26 J=1,NSTRE
      IF(I.EQ.J) GOTO 26
      AMATX(K,J) = AMATX(K,J)+AMATX(K,I)*AMATX(I,J)
    26 CONTINUE
    AMATX(K,I) = FACTR*AMATX(K,I)
  25 CONTINUE
  AMATX(I,I) = FACTR
23 CONTINUE
RETURN
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR MATRICE MULTIPLICATION
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!NSTRE : DIMENSION OF MATRIX
!MATX1 : FIRST MATRIX
!MATX2 : SECOND MATRIX
!MATX3 : SOLUTION MATRIX
SUBROUTINE MATMULT(NSTRE,MATX1,MATX2,MATX3)
INTEGER NSTRE
DOUBLE PRECISION
MATX1(NSTRE,NSTRE),MATX2(NSTRE,1),MATX3(NSTRE,1)
DO 27 j=1,NSTRE
  MATX3(j,1)=0
  DO 28 i=1,NSTRE
    MATX3(j,1)=MATX3(j,1)+MATX1(j,i)*MATX2(i,1)/2
```

```
  28 CONTINUE
27 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR OUTPUT
!!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT NUMBER
!X,Y,Z : COORDINATES OF EACH FINITE ELEMENT
!FLOC : FINAL LENGTH OF CABLE
!R : REACTION OF EACH FINITE ELEMENT
SUBROUTINE OUTPUT1(NOS,FEN,X,Y,Z,FLOC,R)
INTEGER NOS,FEN
DOUBLE PRECISION X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1)
DOUBLE PRECISION FLOC(NOS),R(NOS,FEN+1)
OPEN(34,file='output1.txt')
OPEN(49,file='outputx.txt')
OPEN(61,file='outputy.txt')
OPEN(62,file='outputz.txt')
DO 59 j=1,NOS
  WRITE(34,35)
X(j,1),Y(j,1),Z(j,1),FLOC(j),R(j,1),R(j,FEN+1),X(j,FEN+1),Y(j,FEN+1),Z(j,FEN+1
)
  35 FORMAT(9F50.10)
  DO 51 i=1,(FEN+1)
    WRITE(49,50) X(j,i)
    WRITE(61,50) Y(j,i)
    WRITE(62,50) Z(j,i)
    50 FORMAT(F20.10)
```

```
 51 CONTINUE
59 CONTINUE
CLOSE(34)
CLOSE(49)
CLOSE(61)
CLOSE(62)
END


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR INCREMENTATION CALCULATION AND APPLYING
INCREMENTATION
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!i : SEGMENT LOOP
!NOS : NUMBER OF SEGMENT
!IIOL : IMAGINARY INCREMENTATION ON LENGTH
!R1 : FIRST REACTION OF EACH SEGMENT AND INCREMENTATION
!RLP : LAST REACTION OF EACH SEGMENT AND INCREMENTATION
!LOES : LENGTH OF EACH SEGMENT
!INCR : INCREMENTATION
SUBROUTINE ICAAI(i,NOS,IIOL,R1,RLP,LOES)
INTEGER i,NOS
DOUBLE PRECISION IIOL,R1(NOS,2),RLP(NOS,2),LOES(NOS),INCR
INCR=0
INCR=-IIOL*(R1(i+1,1)-RLP(i,1))/((R1(i+1,2)-RLP(i,2))-(R1(i+1,1)-RLP(i,1)))!/2
ITERATION NUMBER DECREASE TO 1/3 OF IT.
IF(((INCR.GT.0).AND.(INCR.LT.LOES(i))).OR.((INCR.LT.0).AND.(-
INCR.LT.LOES(i+1))))GOTO 106
INCR=-(LOES(i+1)-LOES(i))/2
106 LOES(i)=LOES(i)-INCR
LOES(i+1)=LOES(i+1)+INCR
```

```
END

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!SUBROUTINE FOR SORTING OUTPUT DATA

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!l : INCREMENTATION LOOP

!k : SEGMENT LOOP

!i : FINITE ELEMENT LOOP

!NOS : NUMBER OF SEGMENT

!FEN : FINITE ELEMENT NUMBER

!IX,IY,IZ : IMAGINARLY NONINCREMENTED COORDINATE OF EACH
FINITE ELEMENT

!IR : IMAGINARLY NONINCREMENTED REACTION OF EACH FINITE
ELEMENT

!IFLOC : IMAGINARLY NONINCREMENTED FINAL LENGTH OF CABLE

!X,Y,Z : COORDINATES OF EACH SEGMENT AND EACH FINITE ELEMENT

!FLOC : FINAL LENGTH OF CABLE OF EACH SEGMENT

!R : REACTION OF EACH SEGMENT AND EACH FINITE ELEMENT

SUBROUTINE SOD(l,k,i,NOS,FEN,IX,IY,IZ,IR,IFLOC,X,Y,Z,R,FLOC)

INTEGER l,k,i,NOS,FEN

DOUBLE PRECISION IX(FEN+1),IY(FEN+1),IZ(FEN+1),IR(FEN+1),IFLOC

DOUBLE PRECISION
X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1),R(NOS,FEN+1),FLOC(NOS)

IF(l.NE.1) GOTO 60

X(k,1)=IX(1)

Y(k,1)=IY(1)

Z(k,1)=IZ(1)

R(k,1)=IR(1)

X(k,i+1)=IX(i+1)

Y(k,i+1)=IY(i+1)

Z(k,i+1)=IZ(i+1)
```

```
R(k,i+1)=IR(i+1)
FLOC(k)=IFLOC
60 CONTINUE
END
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR MODULUS OF ELASTICTY
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!STRESS : STRESS OF CABLE ELEMENT
!STRAIN : STRAIN OF CABLE ELEMENT
!S1 : STRESS DATA
!S2 : STRAIN DATA
!MMM : TANGENT MODULUS OF ELASTICTY
SUBROUTINE MODULUS(STRESS,STRAIN)
DOUBLE PRECISION STRESS,STRAIN
DOUBLE PRECISION S1(1000),S2(1000),MMM
INTEGER INDEX
OPEN(67,file='INPUT3.txt')
DO 68 i=1,1000
  READ(67,69)S1(i),S2(i)
  IF (S1(i).GT.STRESS) INDEX=i
    GOTO 70
  69 FORMAT(2F20.10)
68 CONTINUE
70 CONTINUE
MMM=(S2(INDEX)-S2(INDEX-1))/(S1(INDEX)-S1(INDEX-1))
STRAIN=MMM*(STRESS-S1(INDEX-1))+S2(INDEX-1)
CLOSE(67)
END
```

```
!!!!!!!!!!!!!!!!!!!!!
!SUBROUTINE FOR OUTPUT
!!!!!!!!!!!!!!!!!!!!!
!NOS : NUMBER OF SEGMENT
!FEN : FINITE ELEMENT NUMBER
!X,Y,Z : COORDINATES OF EACH FINITE ELEMENT
!FLOC : FINAL LENGTH OF CABLE
!R : REACTION OF EACH FINITE ELEMENT
!REACX : REACTION OF ROLLER SUPPORTS ON X DIRECTION
!REACY : REACTION OF ROLLER SUPPORTS ON Y DIRECTION
!REACZ : REACTION OF ROLLER SUPPORTS ON Z DIRECTION
!REACFX : FIRST END FORCE OF CABLE IN X DIRECTION
!REACFY : FIRST END FORCE OF CABLE IN Y DIRECTION
!REACFZ : FIRST END FORCE OF CABLE IN Z DIRECTION
!REACLX : LAST END FORCE OF CABLE IN X DIRECTION
!REACLY : LAST END FORCE OF CABLE IN Y DIRECTION
!REACLZ : LAST END FORCE OF CABLE IN Z DIRECTION
SUBROUTINE OUTPUT2(NOS,FEN,X,Y,Z,FLOC,R)
INTEGER NOS,FEN
DOUBLE PRECISION X(NOS,FEN+1),Y(NOS,FEN+1),Z(NOS,FEN+1)
DOUBLE PRECISION FLOC(NOS),R(NOS,FEN+1)
DOUBLE PRECISION REACX(NOS+1),REACY(NOS+1),REACZ(NOS+1)
DOUBLE PRECISION REACFX(NOS),REACFY(NOS),REACFZ(NOS)
DOUBLE PRECISION REACLX(NOS),REACLY(NOS),REACLZ(NOS)
DO 71 i=1,NOS
  REACFX(i)=-((X(i,2)-X(i,1))/(FLOC(i)/FEN))*R(i,1)
  REACFY(i)=-((Y(i,2)-Y(i,1))/(FLOC(i)/FEN))*R(i,1)
  REACFZ(i)=-((Z(i,2)-Z(i,1))/(FLOC(i)/FEN))*R(i,1)
```

```
  REACLX(i)=((X(i,FEN+1)-X(i,FEN))/(FLOC(i)/FEN))*R(i,FEN+1)
  REACLY(i)=((Y(i,FEN+1)-Y(i,FEN))/(FLOC(i)/FEN))*R(i,FEN+1)
  REACLZ(i)=((Z(i,FEN+1)-Z(i,FEN))/(FLOC(i)/FEN))*R(i,FEN+1)
71 CONTINUE
REACX(1)=REACFX(1)
REACY(1)=REACFY(1)
REACZ(1)=REACFZ(1)
DO 72 i=1,NOS-1
  REACX(i+1)=REACLX(i)+REACFX(i+1)
  REACY(i+1)=REACLY(i)+REACFY(i+1)
  REACZ(i+1)=REACLZ(i)+REACFZ(i+1)
72 CONTINUE
REACX(NOS+1)=REACLX(NOS)
REACY(NOS+1)=REACLY(NOS)
REACZ(NOS+1)=REACLZ(NOS)
OPEN(73,file='output2.txt')
DO 75 i=1,NOS+1
  WRITE(73,74)i,REACX(i),REACY(i),REACZ(i)
  74 FORMAT(I5,3F20.10)
75 CONTINUE
CLOSE(73)
E
```

APPENDIX B

CODE OF ANSYS MODEL OF SINGLE-SEGMENT CABLE

```
FINISH                  !CLEAR
/CLEAR
/TITLE, SINGLE SEGMENT CABLE
/PREP7                  !PREPROCESSOR DATA SECTION IS OPENED
ET,1,LINK10             !ELEMENT TYPE IS LINK10
KEYOPT,1,2,2            !SMALL STIFFNESS IS ASSIGNED TO SLACK CABLE FOR BOTH LONGITUDINAL AND PERPENDICULAR MOTIONS
KEYOPT,1,3,0            !TENSION ONLY CABLE OPTION
R,1,0.001963495408,0    !CROSS-SECTION AREA OF CABLE IS "0.001963495" AND "0" FOR INITIALLY SLACK CABLE
MP,EX,1,200E9           !MODULUS OF ELASTICITY IS "200E6"
MP,DENS,1,7.85E+3 !DENSITY IS "7.85E3"
MP,ALPX,1,12E-6         !THERMAL COEFFICIENT IN X DIRECTION "12E-6"
MP,ALPY,1,12E-6         !THERMAL COEFFICIENT IN Y DIRECTION "12E-6"
MP,ALPZ,1,12E-6         !THERMAL COEFFICIENT IN Z DIRECTION "12E-6"
K,1,0,0,0               !DEFINITION OF KEYPOINTS
K,2,18,0,0
LSTR,1,2                !DEFINITION OF STRAIGT LINE
LESIZE,ALL,,,10000!NUMBER OF ELEMENTS IS "100"
```

```
LMESH,ALL          !MESHING
FINISH             !PREPROCESSOR IS FINISHED
/SOLU              !SOLUTION SECTION IS OPENED
ANTYPE,STATIC      !TYPE OF ANALYSIS IS STATIC
ACEL,0,9.81        !ACCELERATION IN X DIRECTION IS "9.81"
TREF,0             !REFFERENCE TEMPERATURE IS "0"
TUNIF,40           !UNIFORM TEMPERATURE IS "40"
DK,1,ALL,0         !DISPLACEMENT ON FIRST KEYPOINT IS "0" IN ALL DIRECTIONS
DK,2,UX,-8         !DISPLACEMENT ON SECOND KEYPOINT IN X DIRECTION
DK,2,UY,0          !DISPLACEMENT ON SECOND KEYPOINT IN Y DIRECTION
DK,2,UZ,10         !DISPLACEMENT ON SECOND KEYPOINT IN Z DIRECTION
!D,ALL,UZ,0        !DISPLACEMENT ON ALL NODES IS "0"
!F,50,FY,300       !FORCE APPLIED ON ANY NODE
SSTIF,ON           !STRESS STIFFENING ON
NSUBST,300         !NUMBER OF SUBSTEPS IS "300"
NEQIT,200          !NUMBER OF EQUILIBRIUM ITERATIONS IS "200"
KBC,0              !STEPPED LOADING WITHIN A LOAD STEP IS USED INSTEAD OF RAMPED LOADING
EQSLV,SPARSE       !SPARCE DIRECT SOLVER IS USED FOR EQUATION SOLVER DUE TO ILL CONDITION OF PROBLEM
NLGEOM,ON          !LARGE DEFLECTIONS EFFECT IS CONSIDERED
AUTOTS,ON          !AUTO TIME STEPPING IS ON
SOLVE              !SOLUTION
FINISH             !SOLUTION SECTION IS FINISHED
```

/POST1 !GENERAL POSTPROCESSORS SECTION IS OPENED

PLDISP,1 !DISPLAY DEFORMED SHAP

APPENDIX C

CODE OF ANSYS MODEL OF MULTI-SEGMENT CONTINUOUS CABLE

FINISH ! CLEAR PREVIOUS DATA

/CLEAR

/TITLE, MULTI-SEGMENT CONTINUOUS CABLE

/PREP7 ! PREPROCESSOR DATA SECTION IS OPENED

!!

ELNUM=1000 ! Number of elements

!!

!DEFINITION OF ELEMENTS

!!

ET,1,LINK10 ! ELEMENT TYPE IS LINK10 WHICH IS USED TO MODEL CABLES

KEYOPT,1,2,2 ! SMALL STIFFNESS IS ASSIGNED TO SLACK CABLE FOR BOTH LONGITUDINAL AND PERPENDICULAR MOTIONS

KEYOPT,1,3,0 ! TENSION ONLY CABLE OPTION

ET,2,CONTA175 ! NODAL CONTACT IS DEFINED AS CONTA175

KEYOPT,2,2,4 ! LAGRANGE MULTIPLIER ON CONTACT NORMAL AND PENALTY ON TARGET OPTION IS USED

ET,3,TARGE169 ! TARGET SURFACE IS DEFINED AS TARGE169

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!DEFINITION OF REAL CONSTANTS

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

R,1,0.000314,0                          ! CROSS-SECTION AREA OF CABLE IS "0.001963495" AND "0" FOR INITIALLY SLACK CABLE

!R,2,,,,,,,,,,,100000,,,,0.00000001,

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!DEFINITION OF MATERIAL PROPERTIES

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

MP,EX,1,200E9                           ! MODULUS OF ELASTICITY IS "200E6"

MP,DENS,1,(4*7.85E+3)                   ! DENSITY IS "7.85E3"

MP,ALPX,1,12E-6                         ! THERMAL COEFFICIENT IN X DIRECTION "12E-6"

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!DEFINITION OF KEYPOINTS AND LINES

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

K,1,0,0,0

K,2,76.2,0,0

LSTR,1,2

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!ASSIGNING ELEMENTS AND MESHING

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

TYPE,1                                  ! DEFINITION OF CABLE AND MESHING

MAT,1

REAL,1

LESIZE,1,,,ELNUM
```

```
LMESH,1
N,(ELNUM+2),10,-1
N,(ELNUM+3),20,-3
N,(ELNUM+4),30,-6
N,(ELNUM+5),40,-10
N,(ELNUM+6),50,-15
N,(ELNUM+7),60,-21
TYPE,2                                   ! DEFINITION OF CONTACT ELEMENTS
REAL,2
E,(ELNUM+2)
E,(ELNUM+3)
E,(ELNUM+4)
E,(ELNUM+5)
E,(ELNUM+6)
E,(ELNUM+7)
TYPE,3                                   ! DEFINITION OF TARGET AND MESHING
MAT,1
REAL,2
TSHAPE,LINE
E,3,4
EGEN,(ELNUM-2),1,(ELNUM+7)
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
FINISH                                   ! PREPROCESSOR IS FINISHED
/SOLU                                ! SOLUTION SECTION IS OPENED
```

```
!DEFINITION OF ENVIROMENT

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

ANTYPE,STATIC                       ! TYPE OF ANALYSIS IS STATIC

ACEL,0,9.81                         ! ACCELERATION IN X DIRECTION IS "9.81"

TREF,0                              ! REFFERENCE TEMPERATURE IS "0"

TUNIF,40                            ! UNIFORM TEMPERATURE IS "40"

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!ASSIGNING DISPLACEMENTS TO KEYPOINTS AND ELEMENTS

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

DK,1,ALL,0

DK,2,UX,-6.2

DK,2,UY,-28

DK,2,UZ,0

D,(ELNUM+2),ALL,0

D,(ELNUM+3),ALL,0

D,(ELNUM+4),ALL,0

D,(ELNUM+5),ALL,0

D,(ELNUM+6),ALL,0

D,(ELNUM+7),ALL,0

D,ALL,UZ,0                          ! ALL DISPLACEMENTS IN Z DIRECTION IS 0

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!DEFINITION OF SOLUTION OPTIONS

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

SSTIF,ON                            ! STRESS STIFFENING ON
```

NSUBST,30 ! NUMBER OF SUBSTEPS IS "300"

NEQIT,10000 ! NUMBER OF EQUILIBRIUM ITERATIONS IS "200"

KBC,0 ! STEPPED LOADING WITHIN A LOAD STEP IS USED INSTEAD OF RAMPED LOADING

EQSLV,SPARSE ! SPARCE DIRECT SOLVER IS USED FOR EQUATION SOLVER DUE TO ILL CONDITION OF PROBLEM

NLGEOM,ON ! LARGE DEFLECTIONS EFFECT IS CONSIDERED

AUTOTS,ON ! AUTO TIME STEPPING IS ON

!!

SOLVE ! SOLUTION

FINISH ! SOLUTION SECTION IS FINISHED

/POST1 ! GENERAL POSTPROCESSORS SECTION IS OPENED

PLDISP,1 ! DISPLAY DEFORMED SHAPE