Faculty of Engineering

SHAPE OPTIMIZATION OF CABLE - STAYED STRUCTURES

Tay Boon Teck

Bachelor of Engineering with Honours
(Civil Engineering)
2004

Universiti Malaysia Sarawak
Kota Samarahan

fk

BORANG PENYERAHAN TESIS

Judul: Shape Optimization of Cable-stayed Structures

SESI PENGAJIAN: 2000 - 2004

Saya TAY BOON TECK
(HURUF BESAR)

mengaku membenarkan tesis ini disimpan di Pusat Khidmat Maklumat Akademik, Universiti Malaysia Sarawak dengan syarat-syarat kegunaan seperti berikut:

1. Hakmilik kertas projek adalah di bawah nama penulis melainkan penulisan sebagai projek bersama dan dibiayai oleh UNIMAS, hakmiliknya adalah kepunyaan UNIMAS.
2. Naskhah salinan di dalam bentuk kertas atau mikro hanya boleh dibuat dengan kebenaran bertulis daripada penulis.
3. Pusat Khidmat Maklumat Akademik, UNIMAS dibenarkan membuat salinan untuk pengajian mereka.
4. Kertas projek hanya boleh diterbitkan dengan kebenaran penulis. Bayaran royalti adalah mengikut kadar yang dipersetujui kelak.
5. * Saya membenarkan/tidak membenarkan Perpustakaan membuat salinan kertas projek ini sebagai bahan pertukaran di antara institusi pengajian tinggi.
6. ** Sila tandakan (√)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972).

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/ badan di mana penyelidikan dijalankan).

☑ TIDAK TERHAD

Disahkan oleh

(TANDATANGAN PENULIS) (TANDATANGAN PENYELIA)

Alamat tetap: 4A, Lorong Park,
93000 Kuching,
Sarawak.

Assoc. Prof. Dr. Ng Chee Khoon
(Nama Penyelia)

Tarikh: 5/4/2004

Tarikh: 5/4/2004

CATATAN * **Potong yang tidak berkenaan.**
** **Jika Kertas Projek ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/ organisasi berkenaan dengan menyertakan sekali tempoh kertas projek. Ini perlu dikelaskan sebagai SULIT atau TERHAD.**

PKS/2000

This Final Year Project Report entitled "SHAPE OPTIMIZATION OF CABLE-STAYED STRUCTURES" prepared and submitted by TAY BOON TECK in partial fulfillment of the requirement for the Bachelor of Engineering (Civil) is hereby accepted.

Date : 5/4/2004

Assoc. Prof. Dr. NG CHEE KHOON

Project Supervisor

Civil Engineering Program

Faculty of Engineering, UNIMAS

SHAPE OPTIMIZATION OF CABLE-STAYED STRUCTURES

TAY BOON TECK

This project is submitted in partial fulfilment of
the requirements for the degree of Bachelor of Engineering with Honours
(Civil Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2004

Concrete construction
- strain and stresses
Structures analysis

ACKNOWLEDGEMENTS

I owe an obligation to my Final Year Project Supervisor, Dr. Ng Chee Khoon for his constant assistance in the course of the research and valuable comments on the manuscript. Thanks are also extended to UNIMAS lectures who guided me in pursuing engineering knowledge and skills during my Bachelor degree course. These engineering knowledge and skills have been utilized in the completion of this project.

In addition, I would like to thank my family for their encouragement and support.

ABSTRACT

Cable-stayed structures with tensioned cables stretched down from the towers (pylons) to support the girders have been used in the modern bridge construction. Integral action of these structural members leads this new type of structure to the most competitive solution for long span bridges. However, it is a well-known fact that as the span length increases, and hence the tower height, the quantities to go into a structure will increase progressively, as does contribution from the self-weight of the structural members. Thus, this research study involves optimizing the response performances and properties of the concrete fan-shaped cable-stayed structure within the specific requirement and needs with respect to the design variables by examine various height-to-span ratios.

In order to simplify the optimization process, finite element method was utilized for elastic linear analysis to determine the internal loading of this highly statically indeterminate structure. In this study, the symmetrical configuration and loading structure was modeled into two-dimensional shape, in which the girder was divided into a number of beam elements. Whereas, the tower was also modeled into beam element and cables into bar elements. Meanwhile, trial-and-error method has been adopted to determine the minimum required section of the tower and cables for different height-to-span ratio with the stress in the tower and cables treated as constraints.

This study reveals that the optimum shape of the structure can be achieved at the height-to-span ratio of 0.7 by considering the quantity of cable steel only. However, this ratio reduces to 0.65 if the total cost of the structure is considered by

applying unit prices of material for concrete and cable steel. Therefore, the quantity of cable steel plays a major role in determining the optimum shape of the concrete cable-stayed structure.

ABSTRAK

Struktur di mana kabel penyangga yang disambung dari tiang untuk menyokong pelantar telah digunakan dalam pembinaan jambatan moden. Aksi integrasi di antara kabel penyangga, tiang dan pelantar menjadikan struktur baru ini sesuai untuk pembinaan jambatan panjang. Akan tetapi, kuantiti bahan pembinaan dan berat bagi anggota-anggota dalam struktur ini meningkat dengan penambahan panjang rentang dan ketiggian tiang. Oleh itu, projek ini merangkumi pengoptimuman gerakbalas dan sifat-sifat struktur ini yang berjenis konkrit dan berbentuk kipas supaya ia dapat memenuhi kehendak-kehendak tertentu dengan mengkaji pelbagai nisbah tinggi tiang kepada panjang rentang.

Untuk meringkaskan proses pengoptimuman, kaedah elemen terhingga dengan analisis lelurus secara elastik telah digunakan dalam penentuan beban dalaman struktur tak boleh tentu statik ini. Dalam pengajian ini, struktur yang bersimetri dalam susunan anggota-anggotanya dan beban kenaan telah dimodelkan dalam bentuk 2-dimensi di mana pelantar telah dibahagikan kepada sejumlah kuantiti elemen rasuk. Manakala, tiang dan kabel telah dimodelkan dengan menggunakan elemen rasuk dan elemen bar masing-masing. Di samping itu, kaedah cuba-cuba juga digunakan dalam penentuan minimum luas keratan yang diperlukan oleh tiang dan kabel untuk setiap nisbah tinggi tiang kepada panjang rentang dengan syarat bahawa tegasan-tegasan dalam tiang dan kabel tidak melebihi tegasan-tegasan yang dibenarkan.

Pengajian ini mendapati bahawa bentuk optimum bagi struktur yang dimodel boleh dicapai pada nisbah 0.7 jika hanya kuantiti keluli dalam kabel yang

dipertimbangkan. Manakala, nisbah ini berkurang dan mencapai 0.65 jika jumlah kos bagi seluruh struktur diperhatikan dengan mengenakan unit kos bahan ke atas konkrit dan keluli. Jadi, kuantiti keluli dalam kabel memainkan peranan yang penting dalam menentukan bentuk optimum bagi struktur yang dikaji.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATIONS

a	-	Length of the panel in inches
A	-	Area of the structural element
A_c	-	Required optimum area of the cable
A_p	-	Required optimum area of the tower
A_n	-	Cross-sectional area of the n-th cable in in^2
C_c	-	Cost (in RM) of prestressing steel
C_p	-	Cost (in RM) of concrete used in tower
$C_{(c+p)}$	-	Total cost (in RM) of the cable-stayed structure (cable system and tower)
$\mathbf{d}$	-	Node displacement matrix
$\mathbf{D}$	-	Column matrix that represent both the known and unknown displacements
E	-	Modulus elasticity of the element
E'	-	Modulus elasticity of the cable material in psi
f	-	Permissible stress in the cable in psi
F_n	-	Force in the cable in lb
h	-	Height of the tower
H_{pb}	-	Height of the tower below deck level
H_{pt}	-	Vertical height of stay cables (Height of the tower above deck level)
I	-	Moment of inertia of the element
$\mathbf{k}$	-	Member stiffness matrix

$\mathbf{K}$	-	Structure (Global) stiffness matrix
$\mathbf{k_b}$	-	Member stiffness matrix of beam element
$\mathbf{k_c}$	-	Member stiffness matrix of bar element
λ	-	Horizontal distance of a connecting point between a cable and girder measured from the centerline of the tower
L	-	Span length (Half of the mid-span length)
L_b	-	Length of the beam element
L_c	-	Length of the bar element (cable)
n	-	Number of the panel
$\mathbf{q}$	-	Shear force and bending moment matrix
$\mathbf{Q}$	-	Column matrix that represent both the known and unknown loads
S	-	Spacing of stay cables
U_c	-	Unit price (in RM/m^3) of prestressing steel
U_p	-	Unit price (in RM/m^3) of concrete
UL	-	Uniform load applied on the girder
V_c	-	Total volume of material for stay cables
V_p	-	Total volume of material for the tower
W	-	Weight of the n-th cable
α_n	-	Inclination angle of the n-th cable
γ	-	Specific weight of the cable material in lb/in^3
$\sigma_c^{'}$	-	Allowable stress of the cable
$\sigma_p^{'}$	-	Allowable stress of the tower
Δ_{total}	-	Vertical deflection of the connection joint between the n-th cable and girder

Chapter 1

Introduction

1.1 General

Cable-stayed structure is a structure of which comprises an orthotropic deck and stiffening girder with one or more towers (pylons) erected above the main piers. These girders are supported by cables, which are stretched down diagonally from the towers.

In the early part of the nineteenth century, this type of structure was widely used in Western Europe for bridge construction (Troitsky, 1988). However, they actually possessed structural defects and are limited to short span. This was mainly due to the structural analysis of such structures was not fully understood and defects in their construction.

Now that these problems have been solved to a great extent due to the development of electronic computers for the exact solutions of these highly statically indeterminate systems and advancement of bridge construction. As a result, cable-stayed bridge has been developing rapidly and becomes one of the most competitive bridges for main span ranging from 100 to 900 meters (BBR Systems Ltd., n.d.). For example, a bridge with a center span of 890 meter (the Tatara Bridge, 1999, Japan) has been built. It has been proved that in many cases a cable-stayed solution is superior to a suspension bridge. The advantages lie mainly in the increased aerodynamic stability, reduced cost for the abutments and faster, easier construction.

Also, this is caused by many excellent characteristics, and advantages that possessed by this new type of structure. The main structural characteristic of the system is the integral action of the stiffening girders and tensioned inclined cables. Horizontal compressive forces of the cable are taken by the girders and no massive anchorages are required. Therefore, the substructure is very economical. This characteristic permits them to be built on some soft soil bridge sites, on which building of the anchor will dramatically increase the overall cost.

Furthermore, the horizontal surface (bridge deck) usually acts as a simple beam, most commonly in the form of a truss or box beam giving bridges much more lateral stiffness against wind forces and torsional forces. In fact in orthotropic system of cable-stayed bridge, all elements of the roadway and secondary parts of the superstructure participate in the work of the main bridge system. This result in reduction of the depth of the girders and economy in the steel.

Another structural characteristic of this system is that extremely strong but very flexible cables can be used since cables are always in a state of tension. Cables are very economical as they allow a slender and lighter structure, which is still able to span great distance.

However, the performance of such structural characteristics are much influenced by some parameters such as the height of the tower, length of the panels, inclination, number and spacing of the cables.

The height of the tower greatly affects the stiffness of the bridge system. And as the angle of inclination of the cable with respect to the stiffening girder increases, the stress in the cables decrease, as does the required cross-section of the tower and the cables. However, as the height of the tower increases, the length of the cables, and therefore their axial deflection, also increase, as well as the amount of material for tower construction. Also, experience indicates that the length of the panels mostly affects the height of the tower. Moreover, it is evident that using a small number of stay cables leads to large cable forces, which require strong, complicated anchoring devices, and deeper main girder.

1.2 Objective

Due to the above reasons, it is crucial to control such factors in order to permit the cable-stayed structure to perform at their optimum structural behaviour. The purpose of this study is to model various shapes of concrete cable-stayed structure of fan system and conduct a finite element analysis using ANSYS software for shape optimization. Shape optimization of cable-stayed structure is an improvement of a proposed design that results in the best properties (maximize the load bearing capacity while minimize the weight of a structure) for minimum cost by examine an optimum height-to-span ratio.

1.3 Scope of work

The scope of work in this study includes:

(i) determine the shape of a cable-stayed structure for optimization;

(ii) optimization of the shape by varying the tower height above the deck level;

(iii) optimization calculation by volume of material and cost.

Chapter 2

Literature Review

2.1 General

Shape optimization is the determination of the boundary form which best meets the design criteria while simultaneously satisfying all design constraints. Shape optimization is generally associated with structural optimization with constraints imposed on displacement, stress, buckling and/or natural frequency. Thus, optimum design if compared with conventional trial-and-error methods and designer's past experience is a very well established topic in structural engineering to develop appropriate properties of complex structures. However, a large number of application in aerospace, mechanical or car engineering have been developed in the past, the degree of this methodology in civil engineering is still scarce.

2.2 Optimization Techniques

Hafka and Grandhi (1986) and Rozvany et al. (1995) have reviewed shape and topology optimization of continuum structure. Liang et al. (2000, 2001) proposed the performance-based optimization (PBO) method for automatically producing optimal strut-and-tie models in reinforced and prestressed concrete structures with displacement constraint.

After that, the PBO method with mean compliance constraints to the strut-and-tie modeling was extended to a low-rise concrete shearwall with openings and a bridge pier by Liang et al. (2002). The performance objective of the strut-and-tie model optimization is to maintain overall stiffness of structural concrete member and at the same time minimize its weight. This was done by gradually removing underutilized portions from a structural concrete member to improve its performance. The result shows that optimal topologies produced by the PBO technique could be treated as optimal strut-and-tie models for the design and detailing of structural concrete. It was concluded that the PBO technique presented overcomes the limitations of conventional trial-and-error methods for developing strut-and-tie models in structural concrete, and provides concrete designers with an efficient automated design tool for complex design situations.

Kasuga et al. (1995) have done optimization of cable-force adjustment in concrete cable-stayed bridges by the influence of creep. Kasuga et al. (1995) reported that a major difference between steel and concrete cable-stayed bridges is the influence of creep. It was found that the cable forces decrease and the displacements restrained by the cable forces increase while creep is in progress. Also, residual errors in cable forces will give rise to additional displacements and cable-force changes due to creep.

In their research, the work of the cable forces on the girder and tower were chosen as the objective of function and cable forces and elevation of the girders were treated as constraints. Therefore, the optimum adjusting cable forces were obtained by minimizing the amount of work (the product of the adjusting cable force multiplied by the displacement change).

In order to illustrate the procedure of optimization, the optimum adjusting cable forces of two-cable model and model of the Shin-Ayabe Bridge in Kyoto have been examined by the authors. In their study, the following optimization criteria were used:

(i) Criterion I: Minimizing the sum of the square of the adjusting tensioning forces of the cable.

(ii) Criterion II: Minimizing the work due to the adjusting cable force.

(iii) Criterion III: Minimizing the work due to the adjusting cable force and creep.

(iv) Criterion IV: Minimizing the work due to the adjusting tensioning force of the cable.

The authors found that an efficient solution tending to eliminate residual errors which can give rise to additional displacements.

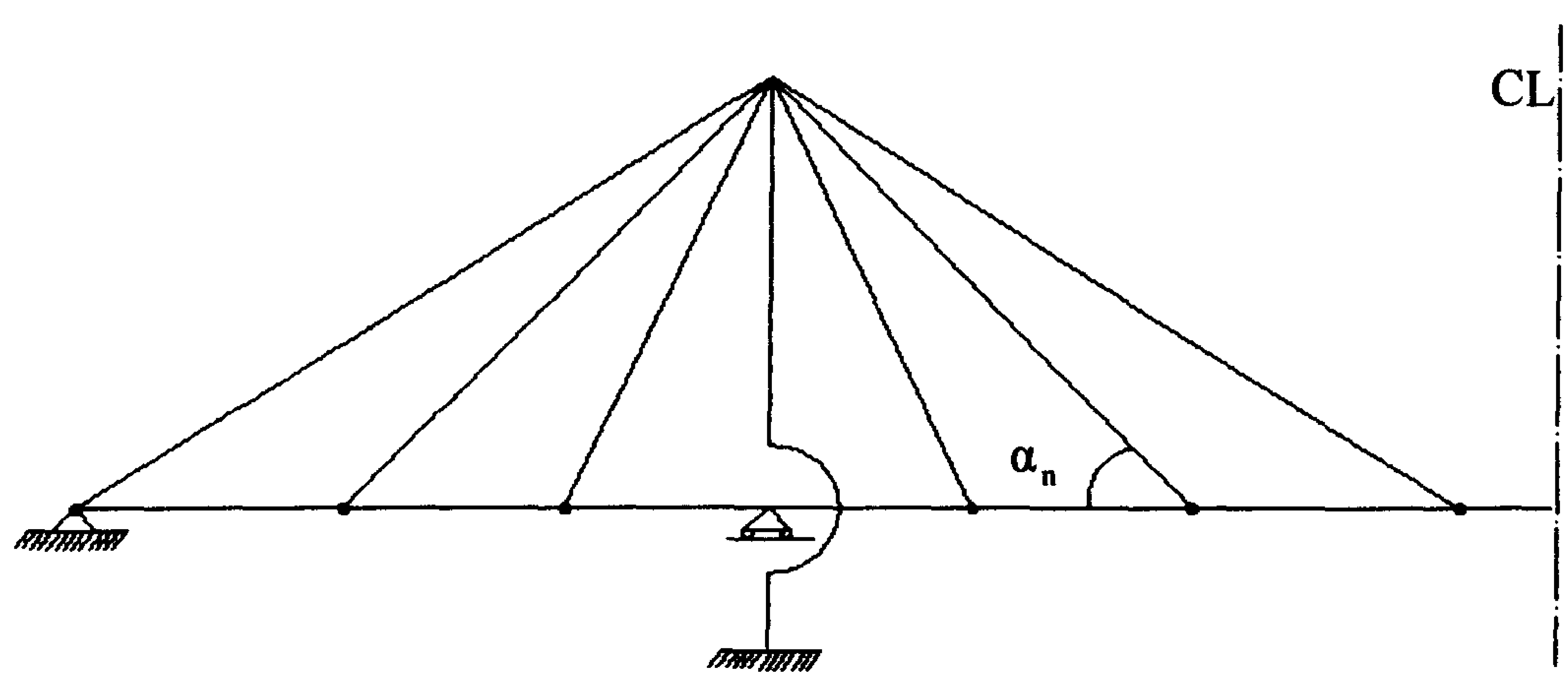

Figure 2.1 Cable-stayed bridge system modeled by Troitsky (1988) for determination of optimum inclination of the cables

Troitsky (1988) noted that the stress in the incline cable of cable-stayed bridge is subjected to the angle of inclination of the cable with respect to the horizontal girder. By assuming the simplified bridge system as shown in Figure 2.1, hinged at the locations of the cable connections to the stiffening girder, the author had developed the formulas of weight of the cable and total vertical deflection of the connection joint between the cable and girder in terms of its inclination angle.

The weight of the n-th cable is given by

$$W = \frac{C_1}{\sin\alpha_n \cos\alpha_n} \tag{2.1}$$

where

$$C_1 = \frac{na\gamma}{f} \tag{2.2}$$

in which n = corresponding number of the panel; a = length of the panel in inches; γ = specific weight of the cable material in lb/in^3; and f = permissible stress in the cable in psi.

Whereas, the vertical deflection of the connection joint between the n-th cable and girder is given by

$$\Delta_{total} = \frac{C_2}{\sin\alpha_n \cos\alpha_n} \tag{2.3}$$

where

$$C_2 = \frac{F_n na}{E' A_n} \tag{2.4}$$

for the symmetrical span, in which F_n = force in the cable in lb; E' = modulus of elasticity of the cable material in psi; and A_n = cross-sectional area of the cable in in^2.

It is shown that, the weight of the cable and the total vertical deflection are dependent upon the inclination angle, and therefore the bending moment, follows the same pattern as the change in the weight of the cable. The values of total vertical deflection, Δ_{total} as function of the angle α_n are shown in Figure 2.2.

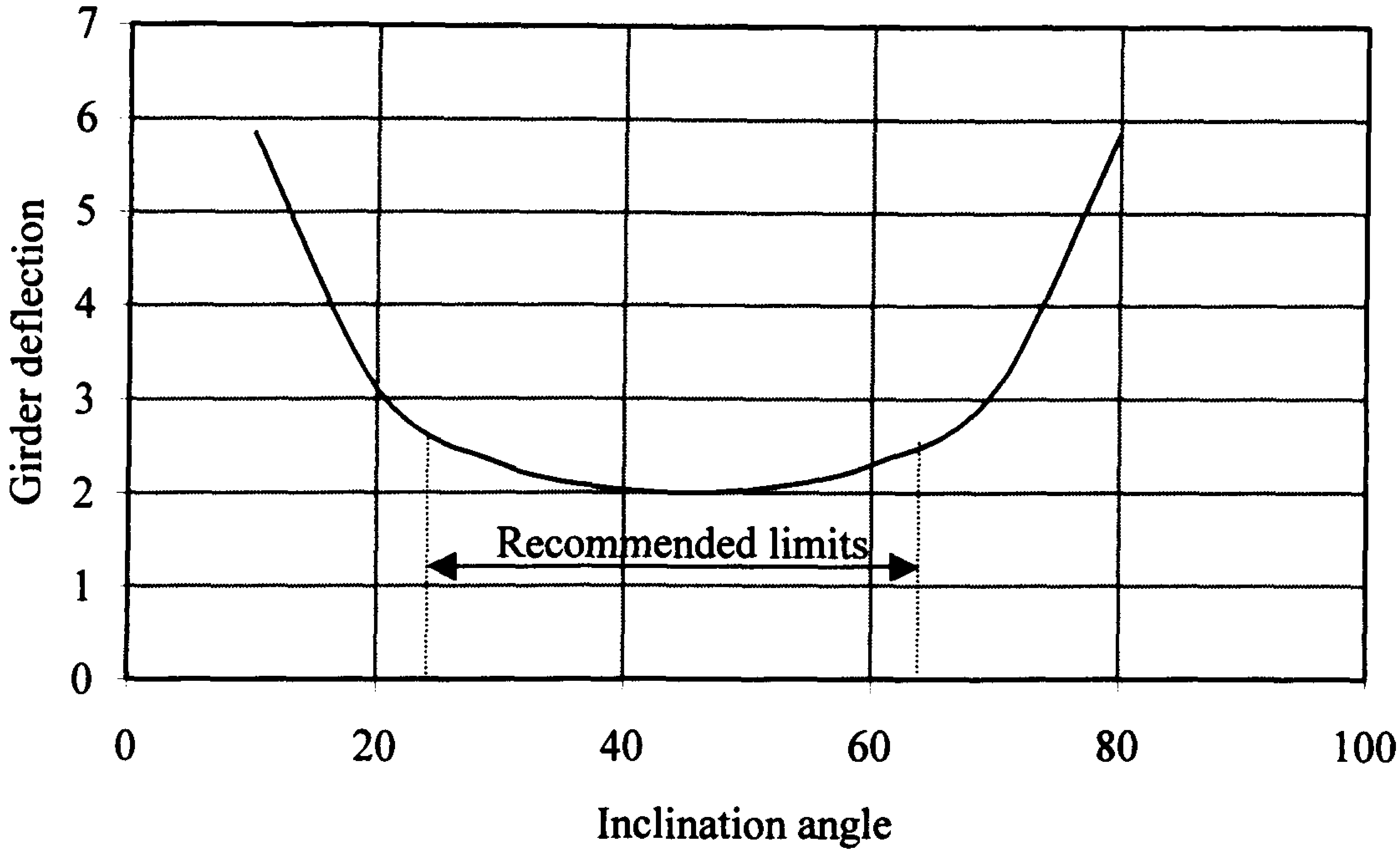

Figure 2.2 Relation between the cable inclination and deflection of the joint

From the diagram, the optimum angle of the cable inclination is 45^0. The author concludes that the inclination angle may vary in the reasonable limits of 25^0 - 65^0 with the low values correspond to the external cable and higher values correspond to the cables nearest to the tower.

By using this optimum angle of the cable inclination, the height of the tower as a function of the span length, may be expressed as

$$h = n \cdot a \cdot \tan 25^0 . \tag{2.5}$$

For usual cable-stayed bridge construction, the following optimum values of the panel length have been adopted.

(i) For the central span in the range 137 – 150 m, panel length is 19.8 m.

(ii) For the smaller central span, the panel should be 15.2 – 16.8 m.

(iii) For central span longer than 168 m, length of panel is 30.5 m long.

It should be noted that the Troitsky's study did not take into account the tower in the optimizing process since the total weight and cost of the cable-stayed