Ain Shams University
Faculty of Engineering

OPTIMUM DESIGN OF LONG-SPAN BRIDGES

BY

MOHAMED AHMED HASSAN HILAL

B Sc. Civil Engineering-Ain Shams University (1991)

M. Sc. Civil Engineering-Ain Shams University (1998)

A THESIS
SUBMITTED IN FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN CIVIL ENGINEERING - STRUCTURAL ENGINEERING

SUPERVISED BY

PROF. DR. MOSTAFA KAMEL ZIDAN

Professor of Structural Engineering
Ain Shams University

PROF. DR. M. NOOR FAYED

Prof. of Structural Engineering
Ain Shams University

DR. MOHSIN F. SHUAIB

Lecturer of Structural Engineering
Menofia University

CAIRO - EGYPT

2007

EXAMINERS COMMITTEE

Name, Title and Affiliation **Signature**

1. **Prof. Dr. Ahmed Abd El-Hameed**
   Dept. of Civil Engineering
   Drexell University- U.S.A. ----------

2. **Prof. Dr. Hassan Ibrahim Hegab**
   Professor of Structural Engineering
   Faculty of Engineering
   Ain Shams University ----------

3. **Prof. Dr. Mostafa Kamel Metwaly Zidan**
   Professor of Structural Engineering
   Faculty of Engineering
   Ain Shams University ----------

4. **Prof. Dr. Mohamed Noor El-Deen Saad Fayed**
   Professor of Structural Engineering
   Faculty of Engineering
   Ain Shams University ----------

Date ----/----/2007

INFORMATION ABOUT THE RESEARCHER

Name MOHAMED AHMED HASSAN HILAL

Date of Birth June 2nd, 1969.

Place of Birth Cairo.

Qualification - B.Sc. Degree in Civil Engineering – Structural Division – General Grade "Excellant with Honor Degree", Faculty of Engineering, Ain Shams University, July 1991.

- M.Sc. Degree in Civil Engineering – Structural Division, Faculty of Engineering, Ain Shams University, Aug. 1998.

Current Job Senior Structural Engineer – Structural Dept.
DAR AL-HANDASAH (SHAIR AND PARTNERS)

STATEMENT

This dissertation is submitted to Ain Shams University for the requirement of the **Degree of Doctor of Philosophy** in Civil Engineering – Structural Engineering.

The work included in this thesis was carried out by, the author in the Department of Civil Engineering (Structural Division), Ain Shams University, from 2000 to 2007.

No part of this thesis has been submitted for a degree or a qualification at any other University or Institution.

Date : June 2007

Name : MOHAMED AHMED HASSAN HILAL

Signature : _____

ACKNOWLEDGEMENT

I wish to express my sincere thanks to ***Prof. Dr. Mostafa Kamel Zidan*** for his direct supervision, generous and continuous support, guidance, encouragement and precise advice to perform this research.

In addition, I am very thankful to ***Prof. Dr. Mohamed Nour El-Din Fayed*** for his kind supervision, generous and constructive criticism, encouragement and cooperation to the full degree during all stages of this work.

I would like to express my great thanks also to ***Dr. Mohsin Fathy Shuaib*** for his kind supervision, throughout the work.

Finally, the author dedicates this thesis to his ***Mother, Uncle, Wife, and Sisters*** for their continuous encouragement, and fruitful care.

AIN SHAMS UNIVERSITY - FACULTY OF ENGINEERING
CIVIL ENGINEERING DEPARTMENT-
STRUCTURAL DIVISION

Abstract of the Doctor of Philosophy Thesis
Submitted by:

Eng. MOHAMED AHMED HASSAN HILAL

Title of the thesis

OPTIMUM DESIGN OF LONG-SPAN BRIDGES

Registration date: 10/3/2003 Examination date: 23/6/2007

Supervisors
Prof. Dr. Mostafa Kamel Metwaly Zidan
Prof. Dr. Mohamed Noor El Deen Saad Fayed
Dr. Mohsin F. Shuaib

ABSTRACT

This thesis deals with the optimum design of long-span bridges. The thesis introduces an extensive survey of the published work on general concepts, history, and different structural types of long-span bridges. An optimization procedure has been proposed for the analysis and design of cable-stayed and suspension bridges, for their minimum weight. The analysis is based on unconstrained minimization of the total potential energy of the structure by conjugate gradient technique. A computational procedure for determining the initial shape of cable-stayed, and suspension bridges, under the action of dead load of the girder and pretension in the inclined cables, is presented. The structure is designed through element level and structural level optimization, using optimality criteria method for member resizing. A proposed optimum geometry design is achieved to satisfy the constraints on both the member and geometrical design variables. A hybrid method is proposed, using the combination of a derived optimality criterion method and the suggested generalized compound scaling algorithm, in order to overcome the associated difficulties in the geometry optimization of the relatively large structures, like the cable-stayed and suspension bridges, which have an increased number of design variables and additional degrees of nonlinearity in the numerical behaviour. This algorithm produces an efficient and a stable optimum geometry design method. Numerical investigations are performed to verify both the efficiency and the mathematical robustness of the proposed algorithm to reach an optimum design**.** Further, emphasis is made particularly on the practical applicability of the proposed optimization algorithm in engineering practice. Applications are made on different types of cable-stayed and suspension bridges, and the obtained results are analysed and discussed.

Key words: Optimum Geometry Design, Initial Shape, Cable-Stayed Bridges.

LIST OF ABBREVIATIONS

CSB	= Cable-stayed bridge
SPCSB	= Spread pylon cable-stayed bridge
SUSB	= Suspension Bridge
OC	= Optimality Criteria method
GCS	= The Generalized Compound Scaling

TABLE OF CONTENTS

Page

STATEMENT
ACKNOWLEDGEMENT
ABSTRACT
TABLE OF CONTENTS i
LIST OF FIGURES ix
LIST OF TABLES xix
LIST OF ABBREVIATIONS xxv
PREFACE xxvi

CHAPTER (1) INTRODUCTION

1.1 GENERAL 1
1.2 BRIDGE TYPES 2
1.2.1 Reinforced Concrete Bridges 2
1.2.2 Steel and Composite Bridges 12
1.3 BRIDGE DECK 18
1.3.1 Concrete Bridge Deck 18
1.3.2 Steel Bridge Decks 25
1.4 BASIS OF ANALYSIS AND DESIGN 25
1.5 LONG–SPAN CABLE–SUPPORTED BRIDGES 32
1.5.1 Cable-stayed bridges 32
1.5.1.1 *Cable arrangements* 33
1.5.1.2 *Deck cross-sections* 36
1.5.1.3 *Tower types* 37
1.5.2 Suspension bridges 37

1.5.3 Future proposed outlines of modern cable supported bridges..... 49
1.5.3.1 Spread pylon cable-stayed bridges type..... 49
1.5.3.2 Cable net bridges 51
1.6 STRUCTURAL ADVANTAGE OF CABLE-STAYED BRIDGES..... 54

CHAPTER (2) REVIEW OF LITERATURE

2.1 HISTORY OF CABLE-SUPPORTED BRIDGES 56
2.2 ANALYSIS OF CABLE-STAYED BRIDGES 78
2.3 STRUCTURAL OPTIMIZATION 94
2.3.1 Introduction 94
2.3.2 Optimality Criteria Technique 97
2.3.3 Approximation concepts 105
2.3.4 Optimum Geometry Design of Structures..... 108
2.3.5 The Generalized Compound Scaling 112

CHAPTER (3) STATIC ANALYSIS OF THREE-DIMENSIONAL STRUCTURES BY ENERGY APPROACH

3.1 INTRODUCTION 114
3.2 ENERGY APPROACH..... 115
3.2.1 Mathematical Formulation..... 117
3.2.2 Gradient Methods for the Determination of Descent Directions..... 122
3.3 NONLINEAR ANALYSIS OF STRUCTURES BY ENERGY MINIMIZATION 139
3.3.1 Assumptions 139

3.3.2 Total Potential Energy in the Displacement Space 139
3.3.3 Gradient Vector of the Total Potential Energy 142
3.3.4 Minimization of the Total Potential Energy 143
3.3.5 An Expression for the Step Length "S" 145
3.3.6 Gradient Vector of the Total Potential Energy 148
3.3.7 Case of Slackening Cables 149
3.3.8 Equivalent Modulus of Elasticity for Cables 149
3.3.9 Numerical ill-Conditioning and Scaling 150
3.3.10 Convergence Criteria 151
3.4 STABILITTY FINITE DEFLECTION THEORY 152
3.5 SUMMARY OF THE ITERATIVE PROCEDURE 155
3.6 ITERATIVE PROCEDURE FOR DETERMINING THE INITIAL SHAPE OF CABLE-STAYED BRIDGES 158
3.7 ILLUSTRATIVE EXAMPLES 160

CHAPTER(4) PROPOSED OPTIMIZATION METHOD AND ITS NUMERICAL VERIFICATION

4.1 INTRODUCTION 168
4.2 OPTIMALITY CRITERIA TECHNIQUE 169
4.2.1 Description of the Method 169
4.2.2 Dominance of Displacement Constraints 170
4.2.3 Dominance of Stress Constraints 173
4.2.4 Dominance of Buckling Constraints 174
4.2.5 Optimum Design Algorithm 175
4.2.6 Convergence Criteria and Oscillation Control 178
4.3 APPROXIMATION CONCEPTS 179
4.4 OPTIMUM GEOMETRY DESIGN OF STRUCTURES 185
4.4.1 Derived Optimality Criterion 185

4.4.2 Suggested Generalized Compound Scaling 191
4.4.3 A Proposed Hybrid Method for Optimum Geometry Design 196
4.4.4 Summary of the Proposed Iteration Procedure for Application to Cable-Stayed Bridges 198
4.5 COMPARATIVE EXAMPLES 202
4.5.1 Example 1: Three-Bar Plane Truss 202
4.5.2 Example 2: Nine-Bar Plane Truss 204
4.5.3 Example 3: 25 Bar Space Truss 208
4.5.4 Example 4: Six storey two bay frame 212
4.5.5 Discussion of the Results 215

CHAPTER (5) CABLE-STAYED BRIDGE MODELS

5.1 INTRODUCTION 217
5.2 MATHEMATICAL MODELS 218
5.2.1 Ordinary Cable-Stayed Bridge Types (CSB) 218
5.2.1.1 Radiating type cable-stayed bridge 218
5.2.1.2 Harp type cable-stayed bridge 220
5.2.2 Spread Pylon Cable-Stayed Bridge Types (SPCSB) 223
5.2.3 Suez-Canal Cable-Stayed Bridge 226
5.3 DESIGN FORMULAE FOR THE STUDIED CABLE-STAYED BRIDGES 232
5.4 LOADING CRITERIA, BEHAVIOUR AND MODELLING TECHNIQUES 236
5.5 DEFLECTION LIMITS 237
5.6 NON-DIMENSIONAL PARAMETERS 238
5.7 ILLUSTRATIVE COMPARATIVE EXAMPLE 238

CHAPTER (6) OPTIMUM DESIGN OF CABLE-STAYED BRIDGES

6.1 INTRODUCTION 243
6.2 OPTIMUM DESIGN OF RADIATING TYPE CABLE-STAYED BRIDGES 243
6.2.1 Optimum Quantities for Different Types of Radiating Bridges 250
6.2.2 Optimum Pylon Height for Radiating Type Cable-stayed Bridges. 250
6.2.3 Percentage of Deck Quantities to Total Bridge Quantities 255
6.2.4 Percentage of Pylon Quantities to Total Bridge Quantities 255
6.2.5 Percentage of Cable Quantities to Total Bridge Quantities 257
6.2.6 Weight Per Square Meter for Different Bridge Types 257
6.2.7 Maximum Pre-Tension Force in Cables 259
6.2.8 Tower Top Displacement 259
6.2.9 Tower Axial Compressive Force 261
6.2.10 Maximum Girder Moment 261
6.2.11 Maximum Tower Moment 263
6.3 OPTIMUM DESIGN OF HARP TYPE CABLE-STAYED BRIDGES 263
6.3.1 Optimum Quantities for Different Types of Harp Bridges 265
6.3.2 Optimum Pylon Height for Harp Type Cable-Stayed Bridges 265
6.3.3 Percentage of Deck Quantities to Total Bridge Quantities 276
6.3.4 Percentage of Pylon Quantities to Total Bridge Quantities 278

6.3.5 Percentage of Cable Quantities to Total Bridge Quantities 278
6.3.6 Weight Per Square Meter for Different Bridge Types..... 280
6.3.7 Maximum Pre-Tension Force in Cables 280
6.3.8 Tower Top Displacement..... 282
6.3.9 Tower Axial Compressive Force 282
6.3.10 Maximum Girder Moment..... 284
6.3.11 Maximum Tower Moment..... 284
6.4 OPTIMUM DESIGN OF SPREAD PYLON TYPE CABLE-STAYED BRIDGES 286
6.4.1 Pylon Height as a Design Variable 286
6.4.1.1Optimum quantities for spread pylon cable- stayed bridges (SPCSB) with variable pylon height..... 286
6.4.1.2 Optimum pylon height for (SPCSB) with variable pylon height 300
6.4.1.3 Percentage of deck quantities to total bridge quantities for (SPCSB) with variable pylon height 300
6.4.1.4 Percentage of pylon quantities to total bridge quantities for (SPCSB) with variable pylon height 302
6.4.1.5 Percentage of cable quantities to total bridge quantities for (SPCSB) with variable pylon height 302
6.4.1.6 Weight per square meter for (SPCSB) with variable pylon height 304
6.4.1.7 Maximum pre-tension force in cables of (SPCSB) with variable pylon height 304
6.4.1.8 Tower top displacement of (SPCSB) with variable pylon height 304

6.4.1.9 Tower axial compressive force of (SPCSB) with variable pylon height 307
6.4.1.10 Maximum girder moment of (SPCSB) with variable pylon height 307
6.4.1.11 Maximum tower moment of (SPCSB) with variable pylon height 307
6.4.2 Spread Angle as a Design Variable 310
6.4.2.1 Optimum quantities for spread pylon cable-stayed bridges (SPCSB) with variable spread angle..... 310
6.4.2.2. Optimum spread angle for (SPCSB) 326
6.4.2.3 Percentage of deck quantities to total bridge quantities for (SPCSB) with variable spread angle..... 326
6.4.2.4 Percentage of pylon quantities to total bridge quantities for (SPCSB) with variable spread angle..... 326
6.4.2.5 Percentage of cable quantities to total bridge quantities for (SPCSB) with variable spread angle..... 329
6.4.2.6 Weight per square meter for (SPCSB) with variable spread angle 329
6.4.2.7 Maximum pre-tension force in cables of (SPCSB) with variable spread angle 331
6.4.2.8 Tower top displacement of (SPCSB) with variable spread angle 331
6.4.2.9 Tower axial compressive force of (SPCSB) with variable spread angle 331
6.4.2.10 Maximum girder moment of (SPCSB) with variable spread angle 334

6.4.2.11 Maximum tower moment of (SPCSB) with variable spread angle 334
6.5 OPTIMUM DESIGN FOR THE SUEZ CANAL CABLE-STAYED BRIDGE..... 334
6.6 COMPARISON OF CABLE QUANTITIES USING APPROXIMATE DESIGN FORMULAE 339

CHAPTER (7) COMPARISON BETWEEN THE SUSPENSION, CABLE-STAYED, AND THE SPREAD-PYLON CABLE-STAYED BRIDGE

7.1 INTRODUCTION 345
7.2 MATHEMATICAL MODELS 346
7.2.1 Model (A) - Radiating Type Cable-Stayed Bridge 346
7.2.2 Model (B) - Harp Type Cable-Stayed Bridge 346
7.2.3 Model (C) - Spread Pylon Cable-Stayed Bridge 346
7.2.4 Model (D) - Suspension Bridge 349
7.3 RESULTS AND DISCUSSION 349
7.4 COMPARISON WITH APPROXIMATE DESIGN FORMULAE FOR CABLE QUANTITIES..... 358

CHAPTER 8 SUMMARY AND CONCLUSIONS 364

REFERENCES..... 373

APPENDIX A LIST OF LONG SPAN BRIDGES AROUND THE WORLD..... A-1

APPENDIX B OPTIMUM DESIGN ALGORITHM SOLVED EXAMPLE..... B-1