

## UNIVERSITI TEKNOLOGI MALAYSIA

**BORANG PENGESAHAN STATUS TESIS\***JUDUL: CASE STUDIES ON FORENSIC STRUCTURAL ENGINEERINGSESI PENGAJIAN: 2005 / 2006Saya NGUEE CHIN SENG  
(HURUF BESAR)

mengaku membenarkan tesis (~~PSM~~ / Sarjana / ~~Doktor Falsafah~~)\* ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hak milik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. \*\*Sila tandakan (√)

SULIT

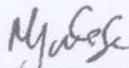
(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

TERHAD

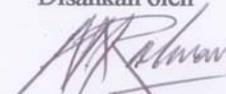
(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/ badan di mana penyelidikan dijalankan)

TIDAK TERHAD

Disahkan oleh



(TANDATANGAN PENULIS)



(TANDATANGAN PENYELIA)

Alamat Tetap:

19, JALAN SUTERA KUNING 7,  
TAMAN SUTERA,  
81200 JOHOR BAHRU, JOHOR.

PROF. DR. AZLAN ABDUL RAHMAN

Nama Penyelia

Tarikh: 2 MAY 2006Tarikh: 2 MAY 2006

## CATATAN:

- \* Potong yang tidak berkenaan.
- \*\* Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/ organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.
- ♦ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

“I hereby declare that I have read this project and in my opinion this project is sufficient in term of scope and quality for the award of the degree of Master of Engineering (Civil-Structure)”

Signature

:

  
.....

Name of Supervisor

:

PROF.DR.AZLAN ABDUL RAHMAN

Date

:

2 MAY 2006

CASE STUDIES ON FORENSIC STRUCTURAL ENGINEERING

NGUEE CHIN SENG

A project report submitted in partial fulfilment of the  
requirements for the award of the degree of  
Master of Engineering (Civil-Structure)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

MAY 2006

I declared that this project report entitled “CASE STUDIES ON FORENSIC STRUCTURAL ENGINEERING” is the result of my own research except as cited in references. This project has not been accepted for any degree and is not concurrently submitted in candidature of any degree.

Signature :  .....

Name : NGUEE CHIN SENG

Date : 2 MAY 2006

*In loving appreciation of my dear family and friends*

*May God shower his blessing on you.*

*Love you forever...*

## **ACKNOWLEDGEMENTS**

I would like to thank all the parties who have given the co-operation to me in writing this project report. I am sincerely grateful to my supervisor, Prof. Dr. Azlan Abdul Rahman for his continuous support and guidance in this project. He has set a high standard for conduct of this study and his valuable suggestions and guidance has provided me the motivation needed to complete this project report.

I thank my family and friends for their support and encouragement. Their encouragement provided the often-need motivation for me to push through the hard times. I would also like to acknowledge the contributions of those who have helped either directly or indirectly in the completion of this project.

## **ABSTRACT**

Forensic engineering is the application of engineering science to the investigation of failure or performance problem. This field of engineering has a big potential in Malaysia as more expertise is required to carry out forensic engineering investigation on failed civil infrastructure. This study involves detailed analysis of methodologies for forensic investigation from four case studies representing different types of structural forms and causes of failure. In order to analyse the case studies, the objectives of investigation of each case study had been derived. In addition, detailed analysis of the failure hypothesis, investigation approaches, causes of failure, modes of failure and application of engineering mechanics that explained the failure mechanism for each case study had also been carried out. The case studies have demonstrated that, although some specific aspects in the methodology may differ from one case to another, the basic element of the methodology remain the same for all cases and it also showed how the selection of appropriate testing methods and analytical techniques can help to confirm the finding and verify the failure hypothesis. The result in terms of comparison between case studies with their different unique features, testing techniques, analytical methods and engineering mechanics are presented in this study. Finally, based on the understanding and analyses of the different features of the case studies, a general guideline of methodology of forensic engineering investigation is proposed. This general methodology is applicable to all forensic engineering investigation to implement best practices in the conduct of forensic engineering investigation, but the specific activities will differ depending on the nature of the problem. Based on the general guideline, the investigators will know the general procedure of the investigation activities involved in the forensic structural investigation.

## ABSTRAK

Kejuruteraan forensik merupakan penggunaan ilmu pengetahuan kejuruteraan untuk menyiasatkan kegagalan atau masalah prestasi sesuatu struktur. Bidang kejuruteraan ini mempunyai potensi yang tinggi di Malaysia memandangkan semakin banyak kepakaran digunakan untuk menjalankan penyiasatan kejuruteraan forensik pada civil infrastruktur. Kajian ini melibatkan dengan menganalisis methodologi penyiasatan forensik pada empat kes yang setiap kesnya menggambarkan perbezaan dari segi bentuk struktur dan sebab kegagalan. Untuk menganalisis kes-kes tersebut, objektif penyiasatan untuk setiap kes telah dibentuk, proses penganalisan yang dijalankan menfokuskan kepada hipotesis kegagalan, cara penyiasatan, sebab kegagalan, gaya kegagalan dan penggunaan mekanik kejuruteraan yang menjelaskan mekanisme kegagalan. Kes-kes yang disiasatkan menunjukkan bahawa walaupun setiap kes mempunyai aspek yang khusus dalam methodologi penyiasatan tetapi asas unsurnya bagi semua kes kekal sama, di samping itu, kes-kes tersebut juga menunjukkan bagaimana memilih cara ujikaji dan kaedah analitis yang sesuai untuk membuktikan hipotesis kegagalan. Keputusan dalam perbandingan perbezaan ciri-ciri, cara ujikaji, kaedah analitis dan mekanik kejuruteraan bagi setiap kes ditunjukkan. Akhirnya, dengan kefahaman dan hasil penganalisan terhadap kes-kes, satu garis panduan umum bagi penyiasatan kejuruteraan forensik diterbitkan. Garis panduan umum ini sesuai digunakan dalam semua penyiasatan kejuruteraan forensik dengan tujuan untuk melaksanakan amalan terbaik dalam penyiasatan kejuruteraan forensik. Dengan merujuk kepada garis panduan umum ini, ahli penyiasat akan tahu prosedur umum bagi aktiviti siasatan yang terlibat dalam penyiasatan kejuruteraan forensik.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGES
	<b>DECLARATION</b>	<b>ii</b>
	<b>DEDICATION</b>	<b>iii</b>
	<b>ACKNOWLEDGEMENTS</b>	<b>iv</b>
	<b>ABSTRACT</b>	<b>v</b>
	<b>ABSTRAK</b>	<b>vi</b>
	<b>TABLE OF CONTENTS</b>	<b>vii</b>
	<b>LIST OF TABLE</b>	<b>xiii</b>
	<b>LIST OF FIGURES</b>	<b>xiv</b>
	<b>LIST OF SYMBOLS</b>	<b>xvi</b>
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Introduction	1
	1.2 Research Significance	2
	1.3 Scope and Objectives of Study	3
	1.4 Methodology	3
	1.5 Content of the Study	4
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>5</b>
	2.1 Definition of Forensic Engineering	5
	2.1.1 Goals of Forensic Engineering Investigation	6
	2.1.2 Qualification of the Forensic Engineer	6
	2.1.2.1 Technical Competency	6
	2.1.2.2 Knowledge of Legal Procedures	7
	2.1.2.3 Detective Skills	7
	2.1.2.4 Oral and Written Communication	8



3.3.2	Collapse	38
3.3.3	Objectives of Investigation	39
3.3.4	Investigation Methodology Flow Chart	40
3.3.5	Failure Hypothesis	41
3.3.6	Investigation Approach	41
3.3.6.1	Site Investigation	41
3.3.6.2	Laboratory Test on the Capacity of Shearhead and Lift Angle	44
3.3.6.3	Computational Analysis of Shear Gaps	44
3.3.7	Cause of Failure	46
3.3.8	Modes of the Failure	47
3.3.9	Engineering Mechanics	48
3.4	Case Study 3: Highland Towers Collapse	49
3.4.1	Background	49
3.4.1.1	Highland Towers and Its Surrounding Features	50
3.4.2	Objectives of Investigation	54
3.4.3	Investigation Methodology Flow Chart	55
3.4.4	Failure Hypothesis	56
3.4.5	Investigation Approach	58
3.4.5.1	Investigation Approach to Support Dr Weeks's Failure Hypothesis	58
3.4.5.2	Investigation Approach to Support Prof Simons's Failure Hypothesis	60
3.4.5.3	Other Investigation Approach that had been Considered by High Court	61
3.4.6	Cause of Failure	63
3.4.7	Modes of the Failure	63
3.4.8	Engineering Mechanics	64
3.5	Case Study 4: Flyover Cracking Problem	67
3.5.1	Background	67
3.5.2	Objectives of Investigation	69
3.5.3	Investigation Methodology Flow Chart	70
3.5.4	Failure Hypothesis	71

3.5.5	Investigation Approach	73
3.5.5.1	Visual Inspection	73
3.5.5.2	Cracking Mapping	74
3.5.5.3	Cover Meter Survey	74
3.5.5.4	Rebound Hammer Test	75
3.5.5.5	Core Test	75
3.5.5.6	Ultrasonic Pulse Velocity (UPV)	75
3.5.5.7	Chemical Analysis	76
3.5.5.8	Design Check	76
3.5.6	Cause of Failure	76
3.5.7	Modes of the Failure	77
3.5.8	Engineering Mechanics	77
<b>4</b>	<b>ANALYSIS OF CASE STUDIES AND DISCUSSION</b>	<b>80</b>
4.1	Introduction	80
4.2	Methodology of Forensic Engineering Investigation	80
4.3	Testing Technique	83
4.4	Analytical Method	84
4.5	Application of Engineering Mechanics	85
4.6	Discussion	86
4.7	Conclusion	87
<b>5</b>	<b>GENERAL GUIDELINE ON STRUCTURAL FORENSIC INVESTIGATION</b>	<b>88</b>
5.1	Introduction	88
5.2	General Flow of Activities	89
5.2.1	Description of General Flow of Activities	90
5.3	Activities in Structural Investigation Work	92
5.3.1	Visual Inspection	92
5.3.1.1	Definition of Visual Inspection	92
5.3.1.2	Purpose of Visual Inspection	92
5.3.1.3	Methodology of Visual Inspection	93
5.3.1.4	Standard and References	94

5.3.1.5 Pro-Forma (Standard inspection Form) for Visual Inspection	95
5.3.2 Eyewitness Interview	96
5.3.2.1 Definition of Eyewitness Interview	96
5.3.2.2 Purpose of Eyewitness Interview	96
5.3.2.3 Information Sought from Eyewitness Interview	97
5.3.2.4 Standard and References	99
5.3.3 Sample Collection	100
5.3.3.1 Definition of Sample Collection	100
5.3.3.2 Purpose of Sample Collection	100
5.3.3.3 Methodology of Sample Collection	101
5.3.3.4 Standard and References	102
5.3.4 Field Testing	103
5.3.4.1 Definition of Field Testing	103
5.3.4.2 Purpose of Field Testing	103
5.3.4.3 Types of Field Testing	104
5.3.4.4 Standard and References	106
5.3.5 Laboratory Testing	108
5.3.5.1 Definition of Laboratory Testing	108
5.3.5.2 Purpose of Laboratory Testing	108
5.3.5.3 Types of Laboratory Testing	109
5.3.5.4 Standard and References	112
5.3.6 Design Check (Document Collection)	115
5.3.6.1 Definition of Design Check	115
5.3.6.2 Purpose of Design Check	115
5.3.6.3 Types of Document needed to Collect and Check	116
5.3.6.4 Standard and References	119
5.3.7 Computational Analysis	119
5.3.7.1 Definition of Computational Analysis	119
5.3.7.2 Purpose of Computational Analysis	119
5.3.7.3 Methodology of Computational Analysis	120
5.3.7.4 Standard and References	121

5.3.8 Development of Failure Hypothesis	121
5.3.8.1 Initial Failure Hypothesis	121
5.3.8.2 Final Failure Hypothesis and Conclusion	121
<b>REFERENCES</b>	<b>122</b>
Appendix- General guideline: Visual Inspection	126
General guideline: Eyewitness Interview	130
General guideline: Sample Collection	135
General guideline: Field testing	139
General guideline: Laboratory Testing	145
General guideline: Design Check	153
General guideline: Computational Analysis	159
Development of Failure Hypothesis	162

**LIST OF TABLES**

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGES</b>
2.1	Specialist consultant (Robert T. Ratay et al, 2000)	16
3.1	Background of the case studies	21
3.2	Chronology of Hyatt Regency Walkways collapse	31
3.3	Loading test result of connections	34
3.4	Shearhead gaps of column	45
4.1	Comparison of case studies	81
4.2	Testing technique of the case studies	83
4.3	Analytical method of the case studies	84
4.4	Engineering mechanics of case studies	85
5.1	Small Tools and Equipment for Visual Inspection	93

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGES
2.1	The investigation process	17
3.1	Investigation methodology of Hyatt Regency Walkways collapse	24
3.2	Photo of walkway sections taken from second floor opening. Walkway sections still remained as a piece-form.	27
3.3	Photo of intact hanger rods from 4 <sup>th</sup> floor walkway opening	28
3.4	Photo of still hanging 3 <sup>rd</sup> floor walkway	28
3.5	General view of the lobby floor, during the first day of the investigation	29
3.6	Photo of one of the walkway cross-beams, lying on the floor of the lobby	29
3.7	Original connection	30
3.8	As built connection	30
3.9	Original and as-built hanger detail	36
3.10	Floor plan of L' Ambiance Plaza (Cuoco et al, 1992)	38
3.11	Status of construction at time of collapse (Cuoco et al, 1992)	39
3.12	Investigation methodology of L' Ambiance Plaza collapse	40
3.13	Scene of L' Ambiance Plaza after collapse	42
3.14	Curing concrete cylinders were found at the L' Ambiance Plaza site (Robert T Ratay, 2000)	43
3.15	Slab to column connection (Cuoco et al, 1992)	45
3.16	Failure sequence (Rachel Martin and Norbert J, 2000)	46
3.17	Scene of Highland towers collapsed	50
3.18	Investigation methodology of Highland Towers collapse	55
3.19	Raking pile	64

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGES</b>
3.20	Simplification raking pile	65
3.21	Force diagram	65
3.22	Force polygon	66
3.23	Cross section of Flyover Bridge	68
3.24	Crack pattern	68
3.25	Scene of flyover at right hand side, during temporary closure which caused massive traffic congestion	69
3.26	Investigation methodology of flyover cracking problem	70
3.27	Crack 1	71
3.28	Crack 2	71
3.29	Crack 3	72
3.30	Crack 4	72
3.31	Visual inspection	74
3.32	Strut and tie model	78
3.33	Example of strut and tie model	78
3.34	Example of result of truss model analysis by using software	79
4.1	General methodology of forensic engineering investigation	82
5.1	General methodology of forensic engineering investigation activities	89
5.2	Pro-Forma for visual inspection	95
5.3	Typical interview questions and information (Robert, A. Ratay, 2000)	99
5.4	Common field tests in structural investigation	106
5.5	Common laboratory tests in structural investigation	112
5.6	Documents used in structural investigation (Kenneth L.Carper, 1989)	117

**LIST OF SYMBOLS**

P	-	Point load
kN	-	Kilo Newton
MN	-	Mega Newton
Ib	-	Pound
mPa	-	Mega Pascal
m	-	Metre
mm	-	Millimetre
ft	-	Feet
in	-	Inch
sec	-	Second
R	-	Reaction force
Q	-	Axial force per length
n	-	Number of the piles
kHz	-	Kilo hertz
T	-	High tensile Bar

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

Forensic engineering is the application of the engineering sciences to the investigation of failures or performance problems. It is a highly specialized field of engineering practice requiring engineering expertise and knowledge of legal procedures. Forensic structural/civil engineers perform “autopsies” on components or full-sized buildings, bridges, and other engineered constructed facilities/infrastructure in order to determine the cause and extent of failure. A secondary purpose is to determine methods of repair, rehabilitation or replacement.

From an engineering perspective, forensic engineering deals with the investigation and reconstruction of failures in buildings, structures, facilities, vehicles, and other engineered systems. From a legal perspective, forensic engineering is a fact-finding mission to learn the most probable cause or causes of a failure.

In order for the forensic engineers to intelligently investigate the cause of a failure and subsequently to identify the parties responsible for it, they have to have an understanding of not only loads, strength and stability, but also of the business and practice of design and construction in order to know where, when, how, why and by whom a cause of failure can originate. They have to know, of course, how to conduct

the investigation appropriate to the case; they must be very familiar to investigation approach. Since nearly all structural deficiencies and failures create claims, disputes, and legal entanglements, forensic engineers need to have some familiarity with the relevant legal process and need to know how to work effectively with attorneys. Complete familiarity with the nature and consequences of loads, and of the critical characteristics and vulnerabilities of structures of different types and materials is the most basic requirement.

## **1.2 Research significance**

Forensic Engineering is a specialised discipline which is relatively new and unfamiliar field to the public. Recently there is increasing number of structural failures which involved forensic investigation to assist legal proceedings related to litigation and damage. This field of engineering has a big potential in Malaysia as more expertise is required to carry out forensic engineering investigation on failed civil infrastructural.

There is a need to carry out studies on:

- 1) Best practices in methodologies for conducting forensic engineering investigation.
- 2) Analysis of case studies on structural failure case studies with engineering significance
- 3) Development and practice of guideline for forensic engineering investigation.

### **1.3 Scope and objectives of study**

The study will involve analysis of four case studies on selected buildings which represent different types of structural forms and also different causes of failure. The study will focus on the methodologies and the applications of engineering mechanics involved in forensic engineering investigation.

The objectives of the study are:

- a) To compare the forensic investigation methodologies of various failure cases.
- b) To evaluate the application of engineering mechanics in forensic structural investigation.
- c) To propose a general guideline on forensic structural investigation failure.

### **1.4 Methodology**

Methodology of this study involves the following stages:

- 1) Identifying suitable case studies  
Selection of suitable case studies covering variety of structures and forms of failures.
- 2) Analysis of selected cases studies  
Analysis on the causes of failure, types of failure, modes of failure, approach on how the investigation are carried out and what the equipment are used in investigation.
- 3) Comparison of methodologies  
Compare each selected cases study on its own methodologies of investigation.

- 4) Evaluate the use of engineering mechanics  
Analyse the application of engineering mechanics to solve failure problems.
- 5) Propose a general guideline  
A general guideline is obtained as outcome.

## **1.5 Content of the study**

The dissertation is divided into 4 chapters as follow:

- 1) Chapter 1: Introduction – State out the background of the research, the objectives and the significance of carrying out the research.
- 2) Chapter 2: Literature Review – Introduction to forensic engineering and other literature study relevant to the study.
- 3) Chapter 3: Case Studies – Detailed analysis of the four selected case studies in order to understand their methodology of forensic engineering investigation, causes of failure, modes of failure and application of engineering mechanics to explain the failure mechanism.
- 4) Chapter 4: Analysis of Case Studies and Discussion – Comparison of the result of the case studies in terms of their methodology of forensic engineering investigation, testing techniques, analytical methods and application of engineering mechanics. A general guideline as an outcome is obtained.
- 5) Chapter 5: General Guideline on Structural Forensic Investigation – Detailed explanation about the general procedures of the activities involved in the structural forensic investigation.