



UNIVERSITI PUTRA MALAYSIA

***EXPERIMENTAL DERIVATION OF STIFFNESS MATRIX OF SHEET
METAL JOINT***

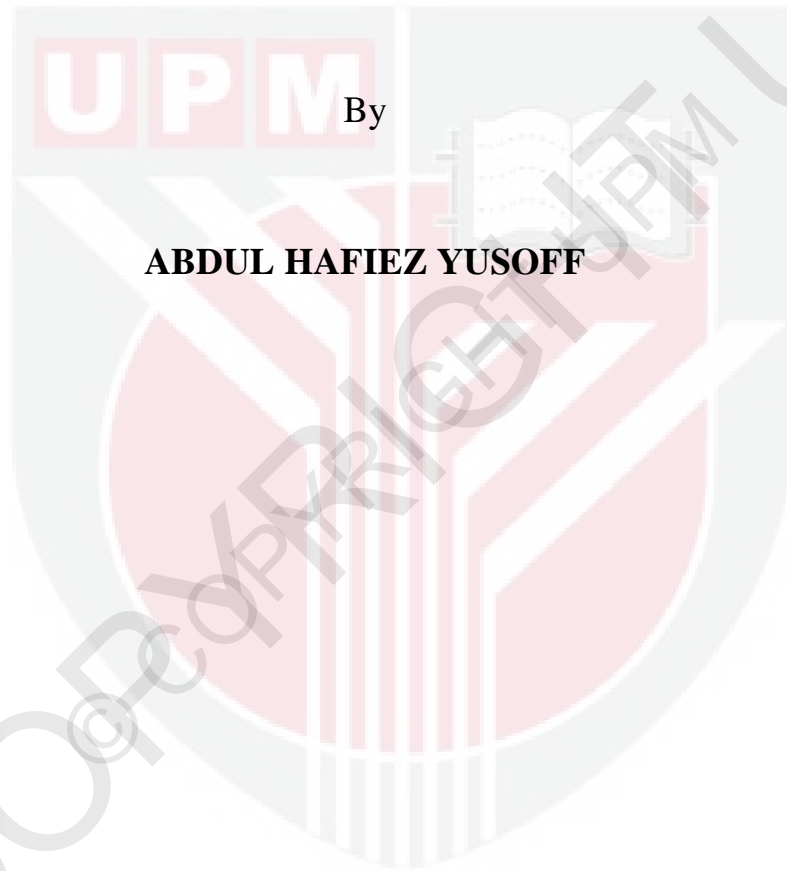
ABDUL HAFIEZ YUSOFF

FK 2013 80

**EXPERIMENTAL DERIVATION OF STIFFNESS MATRIX OF SHEET
METAL JOINT**

By

ABDUL HAFIEZ YUSOFF



March 2013

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

EXPERIMENTAL DERIVATION OF STIFFNESS MATRIX OF SHEET METAL JOINT

By

ABDUL HAFIEZ YUSOFF

March 2013

Chair: Associate Professor Rizal Zahari, PhD

Faculty: Engineering

The thesis presents the study on the three-dimensional experimental derivation stiffness matrix of sheet metal joint substructure based on the basic principle of finite element method (FEM). Normally in FEM, the material properties of a complete structural system can be represented by Young's modulus, Poisson's ratio, density, surface area and etc but if the structure deflection influence coefficients or stiffness matrix are known, the behavior of complete structural system can be defined. One of user defined element existed in NASTRAN that rarely used is general (GENEL) element, the GENEL entry is used to define general elements whose material properties are defined in terms of deflection influence coefficients or stiffness matrix which can be connected between any number of grid points. A systematic approach of stiffness matrix extraction of a sheet metal joint has been successfully studied and developed. The experimental

stiffness matrix which represents the actual behavior of the substructure is then entered into NASTRAN as a new element, GENEL. Comparison of results between the experimental and the finite element analysis is carried to validate the method employed. Excellent agreement with the experimental results has been observed which confirms the accuracy of the approach employed. The methodology of extraction stiffness coefficients experimentally has also been successfully developed on the basis of the direct stiffness method.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan ijazah Sarjana Sains

**UJIKAJI PENERBITAN MATRIKS KEKAKUAN UNTUK PENYAMBUNG
KEPINGAN LOGAM**

Oleh

ABDUL HAFIEZ YUSOFF

Mac 2013

Pengerusi: Profesor Madya Rizal Zahari, PhD

Fakulti: Kejuruteraan

Tesis ini menerangkan ujikaji penerbitan matriks kekakuan untuk penyambung kepingan logam berdasarkan prinsip-prinsip asas dalam analisis unsur terhingga (FEA). Kebiasaannya dalam FEA, sifat bahan untuk sesuatu sistem struktur diwakili oleh modulus Young, nisbah Poisson, ketumpatan, luas permukaan, dan lain-lain tetapi sekiranya nilai pekali pesongan atau matriks kekakuan diketahui, kelakuan sesebuah sistem struktur dapat diramalkan. Salah satu unsur yang dapat diatur cara oleh pengguna dalam NASTRAN ialah GENEL. GENEL merupakan unsur yang amat jarang sekali digunakan oleh pengguna dalam NASTRAN kerana pengguna perlu memasukkan sendiri nilai pekali pesongan atau matriks kekakuan ke dalam NASTRAN. Satu kaedah sistematik telah dibangunkan untuk mendapatkan matriks kekakuan secara ujikaji dan terbukti telah berjaya. Matriks kekakuan yang diperoleh secara ujikaji kemudiannya

akan dimasukkan ke dalam NASTRAN sebagai unsur baru yang dikenali sebagai GENEL. Hasil perbandingan keputusan analisis antara ujikaji dan analisis unsur terhingga menunjukkan tidak banyak perbezaan antara keduanya dan ini mengesahkan ketepatan kaedah yang telah dibangunkan.



ACKNOWLEDGEMENTS

Alhamdulillah, thank to Allah almighty and Merciful for giving me strength and patience in completing this research. Despite difficulties and problems I manage to give my best for this project.

I would like to extend my deepest gratitude to Associate Professor Dr. Rizal Zahari and respectively committee member, Associate Professor Dr. Faizal Mustapha for technical guidance, critical discussion and support throughout my research. Their concern, expert advice and earnest guidance have been priceless throughout the entire project. Further recognition is due to the excellent staff members of Material Strength Laboratory, Production Technology and Automation Laboratory, and Materials Manufacturing Laboratory, Universiti Putra Malaysia, and Mr. Abdullah Sharif of Department of Mechanical and Material Engineering, Universiti Kebangsaan Malaysia for all assistance and advices in completing this research. Finally, I would like to thank my parents and friends for their encouragement and endless support.

APPROVAL SHEET 1

I certify that a Thesis Examination Committee has met on 7 March 2013 to conduct the final examination of Abdul Hafiez Yusoff on his thesis entitled “**Experimental Derivation of the Stiffness Matrix of Welded Tube Joint**” in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Member of the Thesis Examination Committee were as follows:

Harijono Djojodihardjo, PhD

Professor Ir.
Engineering Faculty
Universiti Putra Malaysia
(Chairman)

Mohd Sapuan b. Salit, PhD

Professor Ir.
Engineering Faculty
Universiti Putra Malaysia
(Internal Examiner)

Mohd Khairol Anuar b. Mohd Ariffin, PhD

Associate Professor
Engineering Faculty
Universiti Putra Malaysia
(Internal Examiner)

Nik Abdullah Nik Muhamed, PhD

Professor Ir.
Faculty of Engineering
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

Seow Heng Fong, PhD

Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Rizal Zahari, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Faizal Mustapha, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I declare that the thesis is my original work except for quotation and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.



ABDUL HAFIEZ YUSOFF

Date: 7 March 2013

TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGMENT	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xvii
CHAPTER 1 : INTRODUCTION	1
1.1 : Background of Study	1
1.2 : Problem statement	3
1.3 : Justification for the study	4
1.4 : Objectives	5
1.5 : Scope of study	5
CHAPTER 2 : LITERATURE REVIEW	6
2.1 : Stiffness matrix	7
2.2 : Finite element method (FEM)	10
2.2.1 Review of the finite element method (FEM)	10

2.2.2	General (GENEL) element	14
2.3	Structural joint	15
CHAPTER 3 : METHODOLOGY		17
3.1	Formulation of direct stiffness method	17
3.1.1	: Stiffness matrix	18
3.1.2	: The sheet metal joint stiffness coefficients	25
3.1.3	: Stiffness matrix reduction	28
3.2	: Experimental set up	31
3.2.1	Welded sheet metal joint characteristic	31
3.2.2	: Experimental design	32
3.2.3	: Force at x direction	35
3.2.4	: Force at y and z direction	36
3.2.5	: Torque at x axis	39
3.2.6	: Bending moment at y and z axis	41
3.2.7	: Experimental method	44
3.3	GENEL in NASTRAN	45
3.3.1	: Verification of results using finite element analysis (FEA)	47
3.4	Flow chart methodology	50
CHAPTER 4 : RESULTS AND DISCUSSION		51

4.1	: Experimental analysis	51
4.2	Validation of GENEL	59
4.3	: Case study	64
4.3.1	: Case study: L-shaped structure	65
4.3.2	: Case study: Stadium roof	69
4.3.3	: Case Study: Space frame structure	73
CHAPTER 5	: SUMMARY, CONCLUSION, AND RECOMMENDATION FOR FUTURE RESEARCH	77
5.1	: Conclusion	77
5.2	: Limitation	78
5.3	: Research contribution	79
5.4	: Recommendation for future research	80
REFERENCES		81
APPENDICES		83
APPENDIX A: DETAILED DRAWING		83
APPENDIX B: FORMAT OF GENEL		89
APPENDIX C: NASTRAN PROGRAM STATEMENT FROM EXTRACTED STIFFNESS COEFFICIENTS		90
APPENDIX D: GENEL RESULT		96
APPENDIX E: L-SHAPE STRUCTURE		108
APPENDIX F: STADIUM ROOF DESIGN		109

APPENDIX G: SPACE TRUSS	110
BIODATA OF STUDENT	112
PUBLICATION	113



LIST OF TABLE

	Page
Table 3-1: Description of translational test rig component	38
Table 3-2: Description of rotational test rig component	43
Table 4-1: Experimental reaction forces and moment	53
Table 4-2: Mechanical and geometrical parameter of the specimen	65
Table 4-3: Displacement in x direction	68
Table 4-4: Stadium roof displacement	73
Table 4-5: displacement of space frame structure	76

LIST OF FIGURES

	Page
Figure 2-1: Summary of PATRAN-NASTRAN workflow (MSCSoftwareCorporation, 2007)	11
Figure 2-2: Structural analysis computational flow (Gallagher, 1975)	13
Figure 3-1: Formation of a global stiffness coefficient k_{ij}	20
Figure 3-2: General individual structure member	20
Figure 3-3: Element with n degree of freedom	21
Figure 3-4: The degree of freedom at end of an element	24
Figure 3-5: General member in space	29
Figure 3-6: Welded sheet metal joint axes	32
Figure 3-7: Applying δ_{x2} and obtaining reaction forces and moments	33
Figure 3-8: Applying δ_{y2} and obtaining reaction forces and moments	33
Figure 3-9: Applying δ_{z2} and obtaining reaction forces and moments	33
Figure 3-10: Applying θ_{x2} and obtaining reaction forces and moments	34
Figure 3-11: Applying θ_{y2} and obtaining reaction forces and moments	34
Figure 3-12: Applying θ_{z2} and obtaining reaction forces and moments	34
Figure 3-13: View of specimen with jig for x-direction force during experiment	36
Figure 3-14: Symmetry cross section	37
Figure 3-15: View of test rig for y axis applied force	38

Figure 3-16: View of specimen with test rig for y and z direction force during experiment	39
Figure 3-17: View of specimen with jig for torque	40
Figure 3-18: View of specimen with jig for x-axis rotational displacement during experiment	41
Figure 3-19: View of test rig for y-axis and z-axis bending moment	42
Figure 3-20: View of specimen with test rig for x and y axis rotational displacement during experiment	43
Figure 3-21: PATRAN-NASTRAN workflow and files.	47
Figure 3-22: Structure of the MSC NASTRAN Input File	49
Figure 3-23: Flow chart methodology	50
Figure 4-1: Sheet metal joint axes	51
Figure 4-2: Translation in x direction	59
Figure 4-3: Translation in y direction	60
Figure 4-4: Translation in z direction	60
Figure 4-5: GENEL percentage error of translational axis	61
Figure 4-6: Rotation in x direction	62
Figure 4-7: Rotation in y direction	62
Figure 4-8: Rotation in z direction	63
Figure 4-9: GENEL percentage error rotational axis	64
Figure 4-10: L-shaped structure geometry	66
Figure 4-11: L-shaped structure geometry with GENEL	67

Figure 4-12: L-shaped structure	67
Figure 4-13: L-shaped structure with GENEL	68
Figure 4-14: Stadium roof with field score board	70
Figure 4-15: Stadium roof design modeling geometry	71
Figure 4-16: Stadium roof with GENEL design modeling geometry	71
Figure 4-17: Stadium roof displacement magnitude (deflection)	72
Figure 4-18: Stadium roof displacement magnitude (deflection)	72
Figure 4-19: Space frame structure geometry modeling	74
Figure 4-20: Space frame with GENEL geometry modeling	74
Figure 4-21: Space frame displacement magnitude (deflection), loading in z-axis	75
Figure 4-22: Space frame with GENEL displacement magnitude (deflection), loading in z-axis	75

LIST OF ABBREVIATION

DSM	direct stiffness method
FEA	finite element analysis
FEM	finite element method
GENEL	general element



CHAPTER 1 : INTRODUCTION

1.1 : Background of Study

The development of the finite element method (FEM) owes much to the early work of individuals involved in aerospace structural design, and it is not surprising that this field continues to lead in the practical application of the method. Today FEM has been used in wide range of field other than aerospace engineering and expanded in many ways of application.

Mathematical model is essential to solve the geometrical model of a problem in FEM. The mathematical model may have degree of freedom as much as possible, but it should be identical as much as possible to the real structure. Displacement method is a method often used in solving problems in the FEM because it is the basis.

When computers came into use for structural analysis, it was soon recognized that the displacement method could be easily formulated for computer programming, and it has become the dominating approach in FEM (Holland, 1974).

In design stage, FEM is used to analyze structure behavior and predict what would happen under certain loads. One of the methods used to analyze statically indeterminate complex structure is direct stiffness method. As one of the methods of structural analysis, the direct stiffness method, also known as the displacement method or matrix stiffness method, is particularly suited for computer-automated analysis of complex structures including the statically indeterminate type. This is a matrix method that makes use of the members' stiffness relations for computing member forces and displacements in structures. The direct stiffness method is the most common implementation of the FEM ("Direct Stiffness Method," 2010).

Most engineering structure would be a single solid unit of the same material involving one manufacturing operation. However, there is engineering structure to be fabricated as separate components that should subsequently joined aim to facilitate movement from one place to another. Methods used today for joining metallic structural components to others include welding and mechanical fastening (Ankara & Dara, 1994).

Joints in structural system have important role because they represent potential weak points in the structure, the design of the joint can have a large influence over the structural integrity and load-carrying capacity of the overall structure (McCarthy, McCarthy, & V.P. Lawlor, 2005).

This study shall also investigate the application of MSC NASTRAN general (GENEL) elements on a sheet metal joint. The method present in this thesis shall provide a different way of modeling engineering substructure in FEM code NASTRAN.

1.2 : Problem statement

NASTRAN has a wide variety of elements to help user define the physical characteristic of the model. One of the elements that rarely used but has variety application in structural analysis is GENEL. Although the stiffness matrix of most structures can be readily obtained via numerical or computational methods, there are cases where due to the complexity of the material properties or geometry of structure, it is difficult and time consuming to model using numerical techniques accurately. One of the ways to overcome this problem is to obtain the structure's stiffness coefficients experimentally and enter the stiffness matrix in NASTRAN as GENEL. Another advantage of using GENEL is that they can provide means of protecting confidential designs features or secret while allowing only a stiffness matrix representative model to be passed on to a subcontractor. Previously, no works have been done to generate stiffness coefficients experimentally, with the technique provided it will advance our knowledge in experimental design technique. This study would add knowledge in NASTRAN GENEL that has a wide variety of applications.

1.3 : Justification for the study

The finite element approach simulates the structural properties with mathematical equation written in matrix format in FEM code. The GENEL is used to define general elements whose properties are stated in terms of stiffness matrices which can be connected between any numbers of nodes. The part of a structure could be represented by GENEL in term of stiffness matrix of experimentally or simulation measured data.

For confidential design features; GENEL could be used as stiffness coefficients representative model to be passed on to subcontractor. This means that confidential material and design features used by main contractor can be prevented from falling into the hands of subcontractors if the whole structure with components strategically shared between several companies.

The same concept could be applied to a substructure with unknown mechanical property. Stiffness matrix of relevant substructure could be analyzed in NASTRAN by entering experimental stiffness matrix code. In this method, more accurate representation of a substructure behavior could be obtained.

1.4 : Objectives

The main objective of this study is to develop an experimental technique to extract three dimensional stiffness coefficient of a structure. The following research objectives are formulated:

- I. To develop a test rig and procedures for obtaining stiffness matrix of a sheet metal joint experimentally.
- II. To include the experimentally measured stiffness matrix into NASTRAN new element (GENEL).
- III. To integrate GENEL into a complex engineering structure and perform validation against FEA results.

1.5 : Scope of study

The scope of this study is to obtain the stiffness coefficients of a welded sheet metal joint in linear static region experimentally. Experimental work should be limited to linear analysis and statics motions only. Welded sheet metal joint used in the study is welded at both ends and considered homogeneous material. Comparison of results between the experimental and the finite element analysis is carried out via three test cases to validate the method employed.

REFERENCES

- Aja, A. M. (2000). *Sub-modelling Technique For Static Analysis*. Paper presented at the MSC. Software First South European Technology Conference.
- Ankara, A., & Dara, G. (1994). Analysis of structural lap joints in metals. *Materials and Design*, 15(3).
- Bella, D. F. (1995). *DMAP Alters to Add Differential Stiffness and Follower Force Matrices to MSC/NASTRAN Linear Solutions*: The MacNeal-Schwendler Corporation.
- Chen, J.-T., Chou, K.-S., & Hsieh, C.-C. (2007). Derivation of Stiffness and Flexibility for Rods and Beams by Using Dual Integral Equation. *Journal of Engineering Analysis with Boundary Elements*, 32(2008), 108-121.
- Direct Stiffness Method. (2010). Retrieved 16 November, 2010, from http://en.wikipedia.org/wiki/Direct_stiffness_method
- Dirschmid, W. (1981). An Iteration Procedure For Reducing the Expenses of Static, Elastoplastic and Eigenvalue Problems in Finite Element Analysis. *Computer Methods in Applied Mechanics and Engineering*, 35(1982), 15-33.
- Felippa, C. A., Park, K. C., & Filho, M. R. J. (1998). The Construction of Free-free Flexibility Matrices As Generalized Stiffness Inverses. *Journal of Computer & Structures*, 68, 411-418.
- Gallagher, R. H. (1975). *Finite Element Analysis Fundamental*. New Jersey: Prentice-Hall, Inc.
- Gil, B., & Bayo, E. (2007). An alternative design for internal and external semi-rigid composite joints. Part II: Finite element modelling and analytical study. *Science direct*, 30.
- Greenberg, M. L. (1995). *Use of MSC/NASTRAN General Elements In Complex Static Problems*. Ontario: Spar Aerospace Limited.
- Hibbeler, R. C. (2004). *Engineering Mechanics Statics*. Singapore: Prentice Hall.
- Ho, S. V., & Sankar, S. (1980). A computer program for automatic generation of stiffness and mass matrices in finite-element analysis. *Computers & Structures*, 11(3), 147-161.
- Holland, I. (1974). Fundamentals of The Finite Element Method. *Journal of Computers & Structures*, 4, 3-15.
- II, K. N., Sang-Soo, J., & Moon-Young, K. (2005). An Improved Numerical Method Evaluating Exact Static Element Stiffness Matrices of Thin-walled beam-columns On Elastic Foundation. *Journal of Computer & Structures*, 83, 2003-2022.
- Kebir, H., Roelandt, J. M., & Chambon, L. (2006). Dual boundary element method modelling of aircraft structural joints with multiple side damage. *Engineering Fracture Mechanics*, 73.

- Kelly, G. (2005). Load transfer in hybrid (bonded/bolted) composite single-lap joints. *Composite Structures*, 69.
- Khalili, S. M. R., Shokuhfar, A., Hoseini, S. D., Bidkhorji, M., Khalili, S., & Mittal, R. K. (2008). Experimental study of the influence of adhesive reinforcement in lap joints for composite structures subjected to mechanical loads. *International Journal of Adhesion and Adhesive*, 28.
- Lee, C. K., & Hobbs, R. E. (1998). Closed form stiffness matrix solution for some commonly used hybrid finite elements. *Computer and Structures*, 67, 463-482.
- Livesely, R. K. (1964). *Matrix Method of Structural Analysis*: Pergamon Press.
- McCarthy, M. A., McCarthy, C. T., & V.P. Lawlor, W. F. S. (2005). Three-dimensional Finite Element Analysis of Single-bolt, Single-lap Composite Bolted Joints: Part I-model Development and Validation. *Journal of Composite Structures*, 71, 140-157.
- McGuire, W., Gallagher, R. H., & Ziemian, R. D. (2000). *Matrix Structural Analysis* (Second ed.). New York: John Wiley & Sons, Inc.
- Mohr, G. A. (1979). A Contact Stiffness Matrix For Finite Element Problems Involving External Elastic Restraint. *Journal of Computer & Structures*, 12, 189-191.
- Moon-Young, K., Yun, H.-T., & Kim, N.-i. (2003). Exact dynamic and static element stiffness matrices of nonsymmetric thin-walled beam-columns. *Computer and Structures*, 81, 1425-1448.
- MSCSoftwareCorporation. (2007). NAS120 Course Notes.
- MSCSoftwareCorporation. (2008). MD Nastran R3 Quick Reference Guide
- MSCSoftwareCorporation. (2010). Patran User Guide.
- Palaninathan, R., & Chandrasekharan, P. S. (1985). Curved Beam Element Stiffness Matrix Formulation. *Journal of Computers & Structures*, 21(4), 663-669.
- Prokic, A. (2003). Stiffness Method of Thin-walled Beams With Closed Cross-section. *Journal of Computers & Structures*, 81, 39-51.
- Rodriguez, J. L., Alvarez, E. R., & Moreno, F. Q. (2004). Study of the distribution of tensions in lap joints welded with lateral beads, employing three dimensional finite elements. *Computer and Structures*, 82.
- Sritharan, S., Priestley, M. J. N., & Seible, F. (2000). Nonlinear finite element analyses of concrete bridge joint systems subjected to seismic actions. *Finite Elements in Analysis and Design*, 36.
- Woodgate, K. G. (1998). Efficient stiffness matrix estimation for elastic structures. *Computer and Structures*, 69, 79-84.