CHARACTERISTICS OF PLATES EMBEDDED WITH SHAPE MEMORY ALLOY WIRES

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BORANG PENGESAHAN STATUS TESIS♦

JUDUL: CHARACTERISTICS OF PLATES EMBEDDED WITH SHAPE MEMORY ALLOY WIRES

SESI PENGAJIAN: 2007/2008

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A thesis submitted in fulfillment of the award of the master degree of
Master of Mechanical Engineering

Faculty of Mechanical Engineering and Manufacturing
Universiti Tun Hussein Onn Malaysia

APRIL 2008

" I declared that this Master's Degree Project entitled 'Characteristics of Plates Embedded With Shape Memory Alloy Wires' is the result of my own research except as cited in references."

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To my loving father, mother, brother, sister and Sek Eng
My love to you all will always remain…

ACKNOWLEDGEMENT

In doing this thesis, I would like to express my sincere appreciation to my supervisor, Professor Mohd. Imran bin Ghazali who has given me much encouragement and invaluable guidance in order to complete the research project successfully.

In addition, I would like to convey my appreciation to my lecturer Saifulnizan bin Jamian for the guidance and taught me about the shape memory alloy and the simulation. Beside this I also would like to specially thank to Miss Normayati bte Nordin as a proof reader, Mr. Adam bin Masrom, Mr. Mohd Faizal bin Jasman and Mr. Zahrul Hisham bin Othman for helping me to manufacture the mold in this research while Mr. Fazlannuddin Hanur bin Harith and Mr. Mokhtar bin A. Hamid for helping me to prepare specimens. Beside this, I would like to thank to the Mr. Haji Saifulfazad bin Ahmad and Mr. Md. Zainorin bin Kasron for their advice to conduct the test. I am deeply indebted to my family members and my girlfriend for their love, sacrifice, motivation and support given during the course of this research study.

Last but not least, I would like to express my sincere gratitude to those who have contributed directly and indirectly towards the success of this research project.

ABSTRACT

Shape memory alloy (SMA) has the potential to be used in engineering applications. It is widely used as sensors, actuators, dampers and when embedded into composite, it demonstrates some unique mechanical and vibration properties such as the strength and damping of the composite material. In this research, the thermo-mechanical properties of SMA wire, the mechanical properties and vibration characteristics of composites embedded SMA wire were determined. There are two groups of SMA arrangement in the composite to be fabricated; they are without SMA wire and with unidirectional fine SMA wires (Flexinol® wire) oriented at 0^0, 15^0, 30^0 and 45^0 with the volume fraction of 0.08. The characteristics of SMA wire were determined using the Universal Testing Machine. The Young's modulus, stress – strain curve analysis, fundamental frequency at first mode and damping behavior of the SMA embedded composite were also done. Simulation was carried out using MATLAB based on Brinson model and Reddy approach. The results showed that Flexinol® wire has the phase transformation temperatures at 32.84^0C, 44.78^0C, 52.54^0C and 60.90^0C and it agree well with the manufacturer technical data. The Flexinol® wire has Young's modulus during martensite and austenite of 33.16 GPa and 69.59 GPa and the coefficient of stress influence during martensite and austenite of 10.76 MPa/^{0}C and 9.08 MPa/^{0}C. The Young's modulus of the composite is linearly proportional to temperature increment. The maximum fundamental frequency shifted occur at 45^0 for the boundary condition of C-F-F-F and C-F-C-F while for the boundary condition of C-C-C-C were at 15^0, 75^0, 105^0 and 165^0 if compared with the fundamental frequency at 0^0. The overall highest damping occurred when 0.50 A with DC applied at the boundary condition of C-F-F-F.

ABSTRAK

Aloi Memori Bentuk (SMAs) berpotensi untuk digunakan dalam aplikasi kejuruteraan. Ia digunakan secara meluas sebagai penderia, penggerak, peredam dan apabila ditanamkan dalam rencam, ia menunjukkan sifat mekanikal dan sifat getaran yang unik seperti kekuatan dan sifat peredam bagi rencam. Dalam kajian ini, sifat therma-mekanikal bagi dawai SMA, sifat makanikal dan sifat getaran bagi rencam yang ditanam dawai SMA ditentukan. Terdapat dua jenis kumpulan rencam dihasilkan iaitu rencam tanpa SMA dan rencam yang ditanam dengan SMA pada sudut 0^0, 15^0, 30^0 and 45^0 dengan nisbah isipadu 0.08. Sifat dawai SMA dilakukan dengan mesin ujikaji semesta. Modulus Young dan geraf tegasan-terikan, frekuenci asasi pada mode pertama dan sifat redaman bagi rencam yang ditanam dengan SMA turut dilakukan. Simulasi juga dilakukan dengan menggunakan perisian MATLAB berdasarkan model Brinson dan pendekatan Reddy. Keputusan menunjukkan dawai Flexinol® mempunyai suhu penukaran fasa pada 32.84^0C, 44.78^0C, 52.54^0C dan 60.90^0C dan ia selari dengan data teknikal daripada pengilang. Dawai Flexinol® mempunyai modulus Young semasa martensite dan austenite pada 33.160 GPa dan 69.592 Gpa dan pemalar influsi tegasan semasa martensite dan austenite pada 10.761 MPa/^{0}C dan 9.082 MPa/^{0}C. Modulus Young bagi rencam adalah berkadar terus terhadap peningkatan suhu. Frekuensi asasi terpesong paling tinggi pada 45^0 pada keadaan sempadan C-F-F-F dan C-F-C-F manakala untuk keadaan sempadan C-C-C-C adalah pada 15^0, 75^0, 105^0 dan 165^0 jika dibandingkan dengan frekuensi tabii pada sudut 0^0. Manakala bagi pemalar perendam yang tertinggi secara keseluruhannya berlaku pada arus terus 0.50 A pada keadaan sempadan C-F-F-F.

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LIST OF SYMBOLS

$\varepsilon, \varepsilon_x, \varepsilon_y, \varepsilon_z$ - Strain, normal strain in X, Y, Z direction

ε_0 - Initial strain

ε_l - Maximum residul strain

ε_f, ε_m - Strain (fiber, matrix)

$\gamma, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}$ - Shear strain, shear strain in X, Y, Z plane

F, p - Load

F_f, F_m - Load (fiber, matrix)

$\sum M_x, \sum M_y$ - Total moment (in axis-x, in axis-y)

m_x, m_y - Bending moment per unit length in X, Y, Z Cartesian coordinate system

m_{xy}, m_{yx} - Twisting moment per unit length in X, Y, Z Cartesian coordinate system

q_x, q_y - Transverse shearing forces in X, Y, Z Cartesian coordinate system

u, v, w - Displacement components in X, Y, Z direction

$\sum P_z$ - Total load in axis-z

$\sigma, \sigma_x, \sigma_y, \sigma_z$ - Stress, normal stress in X, Y, Z direction

σ_f - Flexural stress

$\dot{\sigma}$ - Stress

σ_0 - Initial stress

σ_f, σ_m - Stress (fiber, matrix)

σ_F, σ_T - Stress due to force, force due to temperature

$\sigma_f^{AS},\sigma_f^{SA}$	-	Stress of SMA fiber (end of austenite to martensite transformation, end of martensite to austenite transformation)
$\tau,\tau_{xy},\tau_{yz},\tau_{xz}$	-	Shear stress, shear stress in X, Y, Z plane
A, A_f, A_m	-	Area, Cross section area (fiber, matrix)
E	-	Young's modulus
E_M, E_A	-	Young's modulus (martensite, austenite)
E_f, E_m	-	Young's modulus (fiber, matrix)
G, G_{xy}, G_{yz}, G_{xz}	-	Shear moduli, Shear moduli in X, Y, Z plane
V_f, V_m	-	Volume ratio (fiber, matrix)
A_s	-	Austenite start temperature
A_f	-	Austenite finish temperature
M_s	-	Martensite start temperature
M_f	-	Martensite finish temperature
ζ	-	Martensite faction
ζ_0	-	Initial martensite faction
ξ_S	-	Stress induced martensite volume fractions
$\dot{\xi}_s$	-	Stress induced martensite volume fractions
ξ_T	-	Temperature-induced martensite volume fractions
ξ_s	-	Indicative of martensite volume fraction at time, t_{n+1} and $\xi_{s,n}$
Ω	-	Phase transformation coefficient
Θ	-	Thermoelastic coefficient
Θ_M, Θ_A	-	Thermoelastic coefficient (martensite, austenite)
T	-	Temperature
T_0	-	Initial temperature
ΔT	-	Changes of temperature applied
d	-	SMA wire diameter (mm)
λ_s	-	Increments of martensite fraction
$\upsilon,\upsilon_x,\upsilon_y,\upsilon_{xy}$	-	Poisson ratio, passion ratio in in X, Y, Z plane
$\nabla^4(a)$	-	$\frac{\partial^4 a}{\partial x^4}+2\frac{\partial^4 a}{\partial x^2\partial y^2}+\frac{\partial^4 a}{\partial y^4}$

$m\ddot{x}$ - inertia force

$c\dot{x}$ - damping force

kx - restoring force

$f(t)$ - excitation force

$[M]$ - System mass matrix

$[K_s]$ - System stiffness matrix

$[K_r]$ - Geometric stiffness matrix due to recovery stress

$[K_T]$ - Geometric stiffness matrix due to thermal stress

ω - Natural frequency

$\{q^0\}$ - Mode shape of vibration

C_M, C_A - Coefficient of martensite, Coefficient of austenite

φ_x , φ_y - Rotations due to the transverse displacement w

θ_x , θ_y - The independent correction rotations for the rotations φ_x and φ_y, and due to shearing effects

L - Length of the element

B - Width of the element

H - Thickness of the element

ξ, η - Natural coordinate

ψ_j^e - Lagrange interpolation functions

$\alpha_T, \alpha, \alpha_a, \alpha_m$ - Thermal expansion coefficient

LIST OF SHORT FORM

APT	-	Active Property Tuning
ASET	-	Active Strain Energy Tuning
CLPT	-	Classical laminate plate theory
CMC	-	Ceramic matrix composite
DSC	-	Differential Scanning Calorimeter
FSDT	-	First-order shear deformation theory
MEKP	-	Methyl Ethyl Ketone Peroxide
MMC	-	Metal matrix composite
NASA	-	National Aeronautics and Space Administration
PE	-	Polyester
PMC	-	Polymer matrix composite
PVDF	-	Polyvinylidene fluoride
SMA(s)	-	Shape memory alloy(s)
TSDT	-	Third-order shear deformation theory
UTM	-	Universal Testing Machine

CHAPTER I

INTRODUCTION

Shape memory alloys (SMAs) nowadays have the potentials to be used in engineering applications and this has drawn deep interests to many researchers to study and develop new technology based on SMAs. SMAs are usually fabricated with other material to form hybrid composite such as epoxy and Kevlar fibers for wing tail (Simpson and Boller, 2002), ferroelectric ceramic for sensing and actuating to reduce structural vibration (Yang, 2000) and glass-reinforced plastic for vibration control (Friend and Mattey, 1999). The selection of the materials depends on the design application. The polymer matrix composite (PMC) that is embedded with the SMAs is primarily fabricated for the purpose of controlling the static and dynamic properties of composite material. In this research, the PMC had been chosen. Different types of fabrications of the SMA based composites are presented in investigating the basic mechanical properties and vibration characteristics, while another composite plate without SMA is fabricated as a reference for analysis. By measuring the mechanical properties and the vibration mode of a clamped cantilever, the influence of all SMAs arrangement and the temperature on the mechanical properties and vibration characteristic can be clearly seen. The unidirectional fine SMA wires are fabricated at 0^0, 15^0, 30^0 and 45^0 for the angle of SMAs to the composite plate. The mechanical properties involved in this study are Young's modulus and stress – strain curve analysis whereas for the vibration characteristic, investigations are carried out on the natural frequency, first mode frequency and damping behavior of the composite plates.

1.1 Background of the project

Shape memory alloys (SMAs) are widely used as sensors, actuators and dampers. The hybrid composites that are embedded with SMAs demonstrate some unique properties or functions such as self strengthening, active modal modification, high damping, damage resistance, control and self healing. As such they can provide tremendous potential in many engineering applications.

The external skin of the high speed aircrafts, rockets and launch vehicles are subjected to intense thermal load due to the aerodynamic heating. The temperature increase of the skin can induce the thermal buckling and dynamic instability. Previous researcher like Park *et al.* (2004) studied on the vibration of thermally post-buckled composite plates embedded with shape memory alloy fibers. They found out that the stiffness of the plate was affected by controlling the volume fraction and the initial strain of the SMA fibers. Further investigation also found that the thermal large deflection decreased by the SMA fibers. Based on the controllability upon natural frequency, critical temperature and thermal deflection, the SMA fibers can be used for the structure application. Park *et al.* (2004) suggested that further study on the SMA fiber angle, volume fraction and initial strain of the SMA should be carried out in order to optimise the design of the composite plate.

Although the shape memory alloys are manufactured and used in the modern smart structure, the major internal problems of shape memory alloy still occur. This is due to the characteristic of shape memory effect which is only limited to motion along the fibers' longitudinal axes (Kelly and Zweben, 2000). The inter-relationship between the angle of SMAs embedded into the composite and the effect of different angle of SMAs embedded into the composite to the vibration characteristic has not been studied and determined by previous researchers. Besides, as reported by NASA, one of the most challenging and comprehensive projects was applying the advanced textile composites to a more complex structures, such as wings and fuselages (Dow and Dexter, 1997). In this research, different types of orientation of the SMA based composites were presented in investigating the basic mechanical properties and vibration characteristics.

In addition, all the parameters suggested by previous researchers (Gilat and Aboudi, 2004 and Patel *et. al.*, 2005) are studied. This includes the study on the effect of the angle orientation of the SMAs to the vibration characteristics of the composite plate.

1.2 Statement of the problem

The characteristics of the SMA wires are not fully provided by the manufacturer which are very important for the design and simulation (Tan *et. al.*, 2007). Differential Scanning Calorimeter (DSC) is one of the famous test to provide the phase transformation temperatures. However due to specimen preparation, DSC may not suitable for the case of pretension (Tan *et. al.*, 2007 and Zak *et. al.*, 2003c). Zak *et. al.* (2003c) had design a jig to replace DSC and with this jig not only the phase transformation temperatures but other parameters such as the coefficient of stress influence and Young's modulus can also be determine. The jig needs to be precisely fabricated and it has the difficulty to control the temperature by using direct current.

In the report made by Kelly and Zweben (2000), the strain of SMA wires is only limited to the longitudinal axes and this caused the orientation of the SMA fabrication to the composite plate becoming an important factor to be considered for optimum design. The effect of the orientations of the SMA wires fabrication to the composite plate was never studied experimentally by any researchers (Huang, 2005, Lu and Weng, 2000, Gao and Yi, 2003, Tan *et. al.*, 2006 and Tan *et. al.*, 2007).

Most of the simulation works that were done do not consider the effect of the heat transfer from the SMA wires to the composite. When heat increases, the standard properties of materials is no longer valid to be used especially for the polymer. Modifications need to be done on the material properties to show the changes due to the temperature increment.

1.3 Statement of hypothesis

The hypotheses of this research are as follows:-

a. Universal Testing Machine can used to replace Differential Scanning Calorimeter and the jig designed by Zak, *et.al.* (2003c) to determine the phase transformation temperatures and other characteristics of the shape memory alloy.
b. The standard material properties are not valid for higher temperature application and with some modification, the results gained from simulation will tally with the experimental results.

1.4 Purpose of study

The objectives of this research are as follows:-

a. To determine the thermo-mechanical properties of shape memory alloy wires.
b. To study the mechanical properties and vibration characteristics of composite plate embedded with shape memory alloy wires.
c. To study the effects on angles of shape memory alloys embedded into the composite to the studied parameters (stress, strain, fundamental frequency, damping characteristic and temperature).

1.5 Importance of the study

A new method has been proposed to determine the characteristics of the shape memory alloy wire. This method can determine other parameters that cannot be determined by DSC such as the Young's modulus and the coefficient of stress influence as well as the phase transformation temperatures. This method can be used by researchers without having the DSC facility to determine the characteristics of SMA wire. The researchers also do not require a precise rig like Zak, *et. al.* (2003c), but can only use the Universal Testing Machine (UTM) to determine the characteristics of SMA wire.

As suggested by the previous researchers, the orientations of the SMA wires to the hybrid composite need to be studied in optimizing the application of the SMA wire to the hybrid composite product (Huang, 2005, Lu and Weng, 2000, Gao and Yi, 2003, Tan *et. al.*, 2006 and Tan *et. al.*, 2007). However, this important factor was never studied by any previous researchers (Tan *et. al.*, 2006). In this research, the orientation of the SMA wires in the composite plate is studied on the fundamental frequency and the damping.

In the simulation, the effect of heat transfer from the SMA wire to the composite structure is taken into account. Some modification on the standard material properties need to be done. These modified material properties have shifted the fundamental frequency with applied temperature.

1.6 Scope of the study

The scopes of the study are as stated below:-

a. The bonding of the shape memory alloy wires is assumed to be perfectly bonded to the polyester matrix. The *rule of mixture* is applied for this case.
b. Brinson's model will be used to predict the amount of recovery stresses.
c. The constitutive and evolutionary equations in the Brinson's model will be used to solve some cases of the shape memory wires.

d. The study is limited to the natural vibration analysis in the simulation with MATLAB. The damping of the structure is not taken into account.
e. The first-order shear deformation plate theory is used.
f. Heat transfer between shape memory alloy and polyester matrix is assumed to have thermal equilibrium. In addition the heat from direct current is also assumed to be transmitted to the composite structure.