UNIVERSITI PUTRA MALAYSIA

AEROELASTIC FLUTTER PERFORMANCE OF SHAPE MEMORY ALLOYEMBEDDED 3D WOVEN COMPOSITE PLATE UNDER SUBSONIC FLOW

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By

DANISH MAHMOOD BAITAB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2021

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chair : **Assoc. Prof. Dayang Laila binti Abang Haji Abdul Majid, PhD**
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Recent advancements in the aeroelasticity of aircraft structures show an increasing trend in using smart materials with composite structures for improved aeroelastic performance. An example is using shape memory alloys (SMAs) to be combined with composite structures either as actuators or for morphing capabilities. SMA has the ability to accommodate strain rather than breakage by unfolding its lattice when a load is applied and also, it generates stresses due to phase transformation from martensite to austenite at higher temperatures. Due to this coupling effect of SMAs in response to load and temperature, SMAs are embedded in laminated composites for improving damping, stiffness and vibrational characteristics. However, SMA embedded laminated composites are poor in through-the-thickness mechanical properties and SMA-induced stresses and temperature can cause delamination of plies that ultimately results in structural failures under high vibrations.

In this research, SMA wires are embedded in the glass-fibre reinforced composites using 3D woven reinforcements to improve tensile and vibrational characteristics. 3D woven reinforcements provides delamination resistance, higher through-the-thickness mechanical properties and a strong grip to SMA wire due to binding yarns of 3D structure in through-the-thickness direction. Three different 3D woven orthogonal interlock configurations having different interlocking pattern of yarns with SMA wire are analysed in terms of tensile, dynamic and aeroelastic flutter properties. These 3D configurations are layer-to-layer (L2L), through-the-thickness (TT), and a modified interlock (MF) structure that provides the strongest grip to SMA wire than L2L and TT. SMA positioning was also evaluated for both dynamic and aeroelastic flutter properties i.e. SMA at mid, near to trailing, and near to leading edge of cantilevered composite plate.

Tensile results showed that embedding SMA wires into structures have significantly improved tensile properties due to the coupling effect of SMA. The vibrational characteristics are also improved by embedding SMA wire and SMA wire at mid has a higher impact on bending mode frequencies while torsional mode frequencies are more affected for SMA wire at near to trailing and leading edge. Interesting results are obtained from aeroelastic testing by wind tunnel test. Activating SMA results in decrement of flutter speed and flutter frequency due to increment in flexibility of the deflected plate in airflow by SMA-induced stresses. However, there is an improvement in post-flutter behavior as the bending and twist limit cycle oscillation (LCO) amplitudes are reduced by activating SMA wire.

Among 3D configurations, L2L displayed the highest increase of 34.9% in Young's modulus as L2L provides more freedom to SMA for generating stresses due to loose grip of yarns to SMA. For dynamic properties, L2L with SMA at mid showed the highest percentage increment of 17%, 11% and 4% in natural frequencies of first three bending modes respectively. For post-flutter behavior, L2L with SMA near to trailing edge showed a significant decrement of 22.2% in twist LCO amplitude while L2L with SMA at mid showed a decrement of 9.5% for bending LCO amplitude. Hence, this work showed that embedding SMA is beneficial for improving tensile and dynamic properties as well as mitigating the post-flutter vibrations but as the consequence of reduced flutter speed and frequency.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PRESTASI AEROELASTIK KIBARAN ALOI MEMORI BENTUK YANG TERBENAM DALAM PLAT KOMPOSIT TENUNAN 3D DI BAWAH ALIRAN SUBSONIK

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Perkembangan terkini dalam struktur aeroelastik pesawat menunjukkan aliran peningkatan dari segi penggunaan bahan pintar dalam struktur komposit untuk meningkatkan prestasi aeroelastik. Contohnya melalui penggunaan bahan aloi memori bentuk (SMA) yang digabungkan dengan struktur komposit sama ada sebagai penggerak atau untuk keupayaan gabungan. SMA memiliki kemampuan untuk menampung terikan berbanding pemecahan dengan merungkaikan kekisi ketika beban dikenakan dan juga menghasilkan tekanan akibat transformasi fasa daripada martensit ke austenit pada suhu yang lebih tinggi. Disebabkan kesan gandingan SMA ini hasil tindak balas terhadap beban dan suhu, SMA yang terbenam dalam komposit berlapis berupaya meningkatkan ciri redaman, kekukuhan dan getaran. Walau bagaimanapun, SMA terbenam dalam komposit berlapis lemah dari segi sifat mekanikal dalam arah ketebalan serta perubahan tekanan dan suhu yang didorong oleh SMA juga akan menyebabkan pemisahan lapisan yang akhirnya mengakibatkan kegagalan struktur di bawah getaran tinggi.

Dalam penyelidikan ini, dawai SMA terbenam dalam komposit bertetulang gentian kaca menggunakan tetulang tenunan 3D dikaji untuk meningkatkan ciri tegangan dan getaran. Tetulang tenunan 3D memberikan ketahanan nyah-lapisan, sifat mekanik yang lebih tinggi merentasi ketebalan dan genggaman kuat pada dawai SMA kerana adanya pengikat benang struktur 3D mengikut arah ketebalan. Tiga konfigurasi tenunan 3D dengan ciri ortogonal saling-mengunci yang berbeza dimana setiapnya mempunyai corak benang saling-mengunci dengan wayar SMA yang berlainan akan dianalisis dari segi sifat tegangan, dinamik dan aeroelastik. Konfigurasi 3D ini terdiri daripada lapisan ke lapisan (L2L), arah ketebalan (TT), dan struktur saling-mengunci yang diubahsuai (MF) yang memberikan genggaman terkuat pada dawai SMA

berbanding dengan L2L dan TT. Kedudukan SMA juga dinilai dari segi sifat kibaran dinamik dan aeroelastik, contohnya; SMA pada kedudukan tengah, dekat dengan pinggir mengekor, dan dekat dengan pinggir depan plat komposit julur.

Keputusan tegangan menunjukkan bahawa pembenaman dawai SMA ke dalam struktur meningkatkan sifat tegangan dengan ketara kerana kesan gandingan SMA. Ciri getaran juga diperbaiki dengan membenamkan dawai SMA dan dawai SMA pada kedudukan tengah mempunyai hentaman tinggi pada frekuensi mod lenturan, manakala frekuensi mod kilasan lebih banyak dipengaruhi oleh dawai SMA pada jarak dekat dengan pinggir mengekor dan dekat dengan pinggir depan. Keputusan yang menarik diperoleh daripada pengujian aeroelastik melalui ujian terowong angin. Pengaktifan SMA menyebabkan susutan kelajuan kibaran dan frekuensi kibaran kerana tekanan yang disebabkan oleh SMA meningkatkan fleksibiliti plat terpesong dalam aliran udara. Walau bagaimanapun, terdapat peningkatan dalam kelakuan pasca-kibaran disebabkan had lenturan dan puncak piuh litar ayunan (LCO) yang dikurangkan melalui pengaktifan dawai SMA.

Di antara konfigurasi 3D, L2L memaparkan peningkatan tertinggi sebanyak 34.9% dalam modulus Young kerana L2L memberikan lebih banyak kebebasan kepada SMA untuk menghasilkan tekanan disebabkan genggaman benang yang longgar ke atas SMA. Dari segi sifat dinamik, L2L bersama SMA pada kedudukan tengah menunjukkan peningkatan peratusan tertinggi iaitu, sebanyak 17%, 11% dan 4% masing-masing pada frekuensi semula jadi berasaskan tiga mod lenturan pertama. Bagi kelakuan pasca-kibaran, L2L bersama SMA dekat dengan pinggir mengekor menunjukkan penurunan ketara sebanyak 22.2% pada puncak piuh litar ayunan (LCO) manakala L2L bersama SMA pada kedudukan tengah menunjukkan penurunan sebanyak 9.5% untuk puncak lenturan litar ayunan (LCO). Oleh itu, hasil kajian ini menunjukkan bahawa pembenaman SMA bermanfaat untuk meningkatkan sifat tegangan dan dinamik serta mengurangkan getaran pasca-kibaran tetapi sebagai akibat penurunan kelajuan serta frekuensi kibaran.

ACKNOWLEDGEMENTS

I would like to express my special thanks of gratitude to my main supervisor, Dr. Dayang Laila Abang Abdul Majid for her constant support and guidance throughout my journey of completing this thesis. Doing research under her supervision gave me various opportunities and experiences in the research and academics field, which I believe will greatly benefit my career and myself in the future. My gratitude also goes to the supervisory committee members, Dr. Ermira Junita Abdullah and Dr. Mohd Faisal Abdul Hamid for all the support.

My gratitude also goes to all supporting lab technicians, especially Mr. Ahmad Saifol, Mr. Mohd Azfar Roslan, Mr. Saffairus Salih, and Mr. Mohd Suhardi (Aerospace Engineering) for assisting my fabrication and experimental work.

Lastly, I want to express my gratitude to all families and friends that had been endlessly supporting my PhD journey. My special thanks to my parents, my wife, my son and siblings for their moral and financial support.

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

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Date: 12 August 2021

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LIST OF ABBREVIATIONS

AFFDL	Air Force Flight Dynamics Laboratory
ASTM	American Society of Testing and Materials
CNT	Carbon Nanotube
CPT	Classical Plate Theory
DAQ	Data Acquisition
DARPA	Defense Advanced Research Projects Agency
DSC	Differential Scanning Calorimetry
FEA	Finite Element Analysis
FG-CNTRC	Functionally Graded Carbon Nanotube Reinforced
FLIR	Forward-Looking Infrared
FRF	Frequency Response Function
FSDT	First-order Shear Deformation Plate Theory
GE	General Electric
GFRP	Glass Fibre Reinforced Polymer
GVT	Ground vibration testing
Hz	Hertz
LEAP	Leading Edge Aviation Propulsion
LCDs	Liquid Crystal Displays
LCO	Limit Cycle Oscillation
L2L	Layer-to-Layer
MF	Modified
MTS	Material Test System
NI	National Instruments
PDMS	Polydimethylsiloxane

RPM	Revolutions Per Minute
SEM	Scanning Electron Microscopy
SMA	Shape Memory Alloys
SME	Shape Memory Effect
SMAHC	Shape Memory Alloy Hybrid Composite
TT	Through-the-Thickness
UAV	Unmanned Aerial Vehicle
VARI	Vacuum-Assisted Resin Injection
VAT	Variable Angle Tow
2D	Two-Dimensional
3D	Three-Dimensional

CHAPTER 1

INTRODUCTION

1.1 Introduction

In aerospace, the study of interactions of airflow with aircraft is very important as this interaction can cause undesirable deformations and structural failures. This study is known as aeroelasticity and classified in static and dynamic aeroelasticity (Ashley, 1970). Structural divergence and flutter are the failure processes that are strongly affected by structural stiffness. The main area of interest is the flutter phenomenon that is a dynamic instability of elastic structure and it is a synchronized interaction between bending mode and twisting mode so that energy is absorbed from the airflow in one mode to increase the amplitude of the other. The wing will absorb energy from the airflow and will act as an increasing bending and torsion flexure until sufficient displacement is achieved and the wing breaks (Donadon & De Faria, 2016). In aircraft, metallic structures are mostly replaced by the composite structures due to their high stiffness and lighter weights (Dutton et al., 2004).

In composite structures, two-dimensional (2D) laminated composites have been used with outstanding success for many years in the aircraft industry (Mouritz et al., 1999; Kalanchiam & Chinnasamy, 2012). Despite the use of 2D laminates over a long period, their use in many structural applications has been limited due to their low through-the-thickness mechanical properties and inferior impact damage resistance as compared to aluminum alloys and steel (Mouritz et al., 1999). The low through-the-thickness properties have limited the use of 2D laminates to the structures, those are subjected to high through-the-thickness and interlaminar shear stresses such as automobiles, wind turbine blades, stringers and stiffeners in aircraft, and pressure vessels. In aeronautic under high vibrations, the delamination of plies occurs for laminated structures that results in structural failure and even more worst results for curved and angled pieces (Umair et al., 2015).

To improve through-the-thickness properties and interlayer fracture resistance, 3D woven interlock structures are used as composite reinforcement (Mishra, 2008; Nawab et al., 2012). 3D woven reinforcements have higher mechanical properties through-the-thickness direction and are used in areas of high-performance applications (Huang et al., 2018). In 3D woven structures, binder yarns travel in through-the-thickness direction to bind the layers with each other and are responsible for higher through-the-thickness properties, higher delamination resistance, and excellent damage tolerance (Mouritz et al., 1999; Khokar, 2001; Lee et al., 2002). Also for 3D structures, the desired properties can be incorporated during the weaving process and these structures can be produced according to the required shape (Soden & Hill, 1998).

Recently, the development of composite materials took advantage of their inherent heterogeneity and anisotropy to combine the traditional load-bearing functions of composite materials with novel functionalities in the form of embedded elements. By combining smart materials with composites, the properties of the resultant smart composites can be modified due to integrating functions of smart materials directly into the structures (Cohades & Michaud, 2018). Among smart materials, shape memory alloys (SMAs) are able to generate a relatively large deformation and then recover their deformed shape upon heating (Liang & Rogers, 1997). At low temperature, SMA actuators are plastically deformed by bending, stretching, compressing and twisting, and they return to their original shape and size by increasing temperature due to internal phase transformation process. This shape reformation process generates a thermal–mechanical driving force (Kim et al., 2011). This shape recovery property of SMA makes it the most suitable smart material for active control of the structures.

SMAs have two phases; the austenite phase having higher Young's modulus due to well-packed crystalline structures at a higher temperature and the martensite phase in which SMAs have loosely packed crystalline structures at a lower temperature and behave as elastomers. In the martensite phase when a load is applied to SMA, it accommodates the strain as its crystal planes unfold the lattice and begin to reorient with the direction of loading. This reorientation of the lattice is known as "detwinning" and it gives higher values of stiffness (Sharifishourabi et al., 2014). SMAs change their phase from martensite to austenite at a higher temperature and recover their residual deformation due to well-packed crystalline arrangement in the austenite phase (Lei et al., 2013). The coupling effect of SMAs in response to temperature and load signifies their importance and encourages their embedment in composite structures for improving structural properties.

Generally, pre-strained SMA wires are embedded into composite structures and the electric current is applied to activate the SMA wires. Due to electric current, resistance heat is generated in the SMA and a large additional internal force would then be induced accordingly into the structures (Kim et al., 2011). This induced internal force in SMA is responsible for improving the bending and torsional stiffness of the SMA embedded composite structures. Improved bending and torsional properties improve the dynamic and aeroelastic characteristics of the structures. Many researches has been carried out for improving dynamic and aeroelastic characteristics of the structures by embedding SMA wires in composites (Barzegari et al., 2012; Samadpour et al., 2016; Donadon & De Faria, 2016; Cao et al., 2017; Lin et al.,2020). These researches are limited to embedding SMA wires in 2D structures and mostly studies are computational work. 2D laminated composites are poor in through-the-thickness mechanical properties and SMA-induced stresses and temperature can cause delamination of plies that ultimately results in structural failures under high vibrations.

In this research, SMA wires are embedded into 3D woven structures for achieving improved mechanical properties due to SMA-induced force and higher through-the-thickness properties due to 3D structure. Further, the dynamics and aeroelastic properties are assessed for 3D woven composite configurations with SMA embedded at different positions to evaluate the effect of SMA and its positioning on the dynamic and aeroelastic performance of the structures.

1.2 Problem Statement

The laminated composites have replaced most of the metallic structures in aircraft due to their light-weight and high strength. During the flight, the aircraft undergoes the aeroelastic effects that can cause structural failure if the stiffness of the structures is not adequate. For achieving higher stiffness, the fibres with higher Young's modulus such as carbon fibres are used as a reinforcement of composite structures. The increment of high-performance fibres for improving stiffness results in brittleness and also increases the cost.

Although the laminated composites reinforced with high-performance fibres have higher in-plane mechanical properties but their through-the-thickness properties are poor and also these structures face delamination of plies when subjected to high vibrations that result in failures of structures (Nawab et al., 2018).

On the other hand, the 3D composites have higher through-the-thickness properties and delamination resistance but their in-plan properties are compromised due to the higher crimps in yarns (Stig & Hallström, 2013). While to prevent aeroelastic effects, the in-plane properties especially the stiffness of the structures should be higher.

SMAs are the smart materials embedded in structures for improving stiffness by activating wires. For embedding SMA wires in laminated composites, additional processes are required for improving interfacial strength between SMA wire and matrix for achieving desired properties (Yang et al., 2018).

Additionally, recent progress works on aeroelastic tailoring using smart materials are explored only for 2D laminated composites. Especially for SMA, most works reported are numerical findings due to the experimental challenges of embedding SMAs into a composite system. These computational studies are related to embedding SMA in resin and fibres and there is no research to date that explains the aeroelastic behavior of SMA-fibre woven composites (Barzegari et al., 2012; Samadpour et al., 2016; Donadon & De Faria, 2016; Cao et al., 2017; Lin et al.,2020).

So, there is a need to develop a smart composite structure for aircraft wing which has higher in-plane as well as through-the-thickness properties with a resistance to delamination and then experimental evaluation of its dynamic and aeroelastic flutter performance.

1.3 Research Objectives

This research has the main objective to improve the mechanical properties of 3D woven composites by embedding SMA wires and evaluate their dynamic and aeroelastic properties. The specific objectives are as follows:

1. To investigate and compare the tensile properties of 2D and 3D woven composite configurations without SMA wire, with inactive and activated SMA wire.

2. To assess the dynamic characteristics of 3D woven composite configurations without SMA wire, with inactive and activated SMA wire at mid, trailing and leading edge.

3. To evaluate the aeroelastic performance of 3D woven composite configurations without SMA wire, with inactive and activated SMA wire at mid, trailing and leading edge.

1.4 Scope of Research

This research is a fundamental structural study to modify the properties of glass-fibre reinforced 3D woven composite by embedding SMA wires. The basic purpose of the study is to improve the mechanical properties of the composite plate by using the stress generation property of SMA wires embedded in 3D woven structure and assess the dynamic and aeroelastic properties of SMA embedded 3D woven composites with improved mechanical properties.

This study is limited to the multi-layer 3D orthogonal interlock with layer-to-layer and though-the-thickness penetration of binding yarns due to the higher bending and shear rigidity of 3D orthogonal structures. The SMA wire is embedded span-wise in the composite plate with a lower volume fraction i.e. 0.389%. The span-wise direction of SMA contributes evenly to improve stiffness of whole structure and the lower volume fraction of SMA minimizes the effects of SMA activation temperature on matrix and fibres. On the other hand, to achieve higher effects of SMA-induced stresses on mechanical, modal and aeroelastic properties, the plate is designed a flexible structure with thickness of 0.7 mm. To keep same volume fraction of SMA wire for the samples of aeroelastic flutter test with tensile test samples, the calculated aspect ratio was 6. Also aspect ratio 6 gives the highly flexible structure whose flutter can be easily manifested under low airspeed.

As the current study is the fundamental experimental research to explore the aeroelastic flutter properties of SMA embedded 3D woven composite plate, the aeroelastic flutter properties are evaluated in subsonic laminar flow of open-circuit wind tunnel with Mach number, M ~ 0.02 and Reynolds number 1.2 x 10^5. The lower Mach number and Reynolds numbers gives the smooth flow in which flutter performance of highly flexible plate can be precisely observed.

1.5 Thesis Layout

The thesis has five chapters in which Chapter 1 gives a brief introduction, objectives and the scope of the current study. Chapter 2 highlights the previous studies related to aeroelasticity and its types followed by a discussion on composites structures and smart materials. The studies related to composite passive tailoring for improving the aeroelastic performance are then presented and finally a discussion on embedding shape memory alloys for active tailoring of composites for improving aeroelastic performance. Chapter 3 is the methodology that described the materials, 3D weaving procedure of SMA embedded 3D structures and their composite fabrication method, testing methods for tensile, dynamic, and wind tunnel tests. Chapter 4 presents the results and discussion for the tensile, dynamic, and aeroelastic properties of SMA embedded 3D woven composites. Chapter 5 addresses the conclusion and recommendations for the future work.

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APPENDICES

Appendix A1. Calculation of volume fraction of constituents of composite structures for tensile test

m_c= 8.36gm, m_f= 6.29gm, ρ_f=2.54gm/cm³, ρ_m=1.1gm/cm³, m_{SMA}=0.108gm, ρ_{SMA}= 6.45 gm/cm³,

For matrix weight,

$$m_c = m_f + m_m + m_{SMA}$$

$$m_m = 1.962\text{gm}$$

1. Fibre volume fraction

$$V_f(\%) = \frac{m_f * \rho_c}{m_c * \rho_f} * 100$$

For calculating density,

$$\rho_c = \frac{m_c}{m_c - m_w} * 0.997$$

Dimensions of composite sample for calculating density are 2 x 2 x 0.07cm³ while dry weight and weight in water are m_c=0.540 gm and m_w =0.262 gm.

$$\rho c = \frac{0.540}{0.540 - 0.262} * 0.997 = 1.937\text{gm/cm}^3$$

$$V_f(\%) = \frac{6.29 * 1.937}{8.36 * 2.54} * 100 = 57.38(\%)$$

2. Matrix volume fraction

M_m= 1.962 gm,

$$V_m(\%) = \frac{m_m * \rho_c}{m_c * \rho_m} * 100$$

$$V_m(\%) = \frac{1.962 * 1.937}{8.36 * 1.1} * 100 = 41.33\%$$

3. SMA volume fraction

$$V_{SMA}(\%) = \frac{m_{SMA} * \rho_c}{m_c * \rho_{SMA}} * 100$$

$$V_{SMA}(\%) = \frac{0.108 * 1.937}{8.36 * 6.45} * 100 = 0.388\%$$

4. Void Content (%)

$$V_v(\%) = 100 - (V_f(\%) + V_m(\%) + V_{SMA}(\%))$$

$$V_v(\%) = 100 - (57.38 + 41.33 + 0.388) = 0.902\%$$

Appendix A2. Calculation of volume fraction of constituents of composite structures for modal analysis and aeroelastic analysis

m_c= 20.055gm, m_f= 15.15gm, ρ_f=2.54gm/cm³, ρ_m=1.1gm/cm³, m_{SMA}=0.26gm, ρ_{SMA}= 6.45 gm/cm³,
For matrix weight,

$$m_c = m_f + m_m + m_{SMA}$$
$$m_m = 4.645\text{gm}$$

1. Fibre volume fraction

$$V_f(\%) = \frac{m_f * \rho_c}{m_c * \rho_f} * 100$$
$$\rho_c = \frac{m_c}{m_c - m_w} * 0.997$$

Dimensions of composite sample for calculating density are 2 x 2 x 0.07cm³ while dry weight and weight in water are m_c=0.544 gm and m_w =0.264 gm.

$$\rho_c = \frac{0.544}{0.544-0.264} * 0.997 = 1.937\text{gm/cm}^3,$$

$$V_f(\%) = \frac{15.15 * 1.937}{20.055 * 2.54} * 100 = 57.61(\%)$$

2. Matrix volume fraction

$$M_m = 1.962 \text{ gm}$$

$$V_m(\%) = \frac{m_m * \rho_c}{m_c * \rho_m} * 100$$
$$V_m(\%) = \frac{4.645 * 1.937}{20.055 * 1.1} * 100 = 40.78\%$$

3. SMA volume fraction

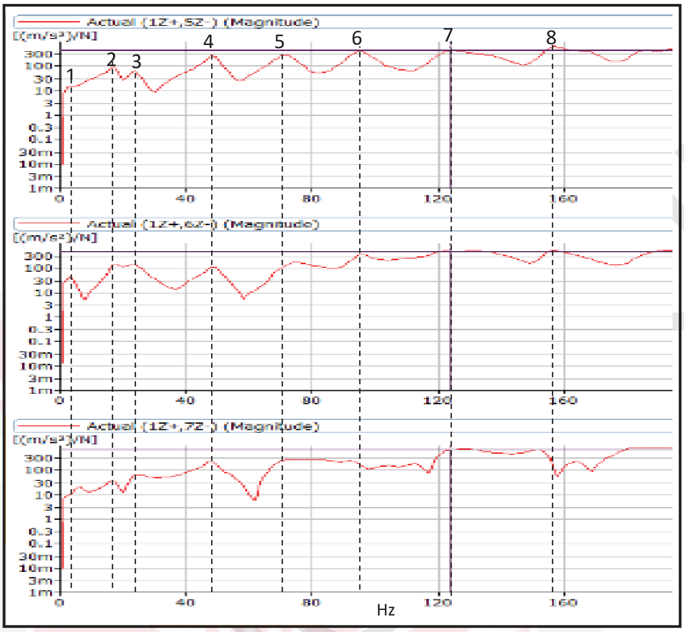
$$V_{SMA}(\%) = \frac{m_{SMA} * \rho_c}{m_c * \rho_{SMA}} * 100$$
$$V_{SMA}(\%) = \frac{0.26 * 1.937}{20.055 * 6.45} * 100 = 0.389\%$$

4. Void Content (%)

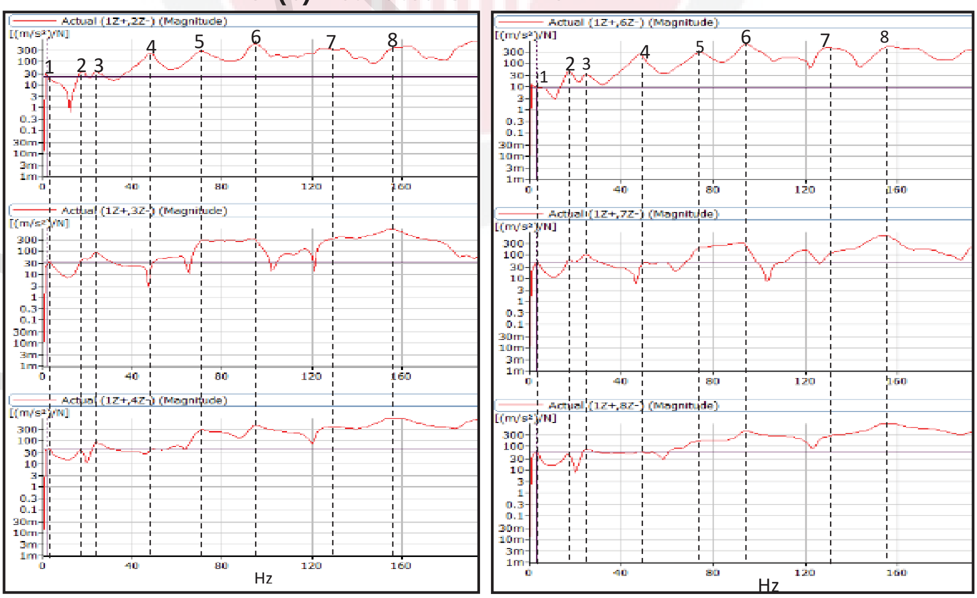
$$V_v(\%) = 100 - (V_f(\%) + V_m(\%) + V_{SMA}(\%))$$
$$V_v(\%) = 100 - (57.61 + 40.78 + 0.389) = 1.221\%$$

Appendix B1

Appendix B1.1. FRF plot of L2L without SMA wire

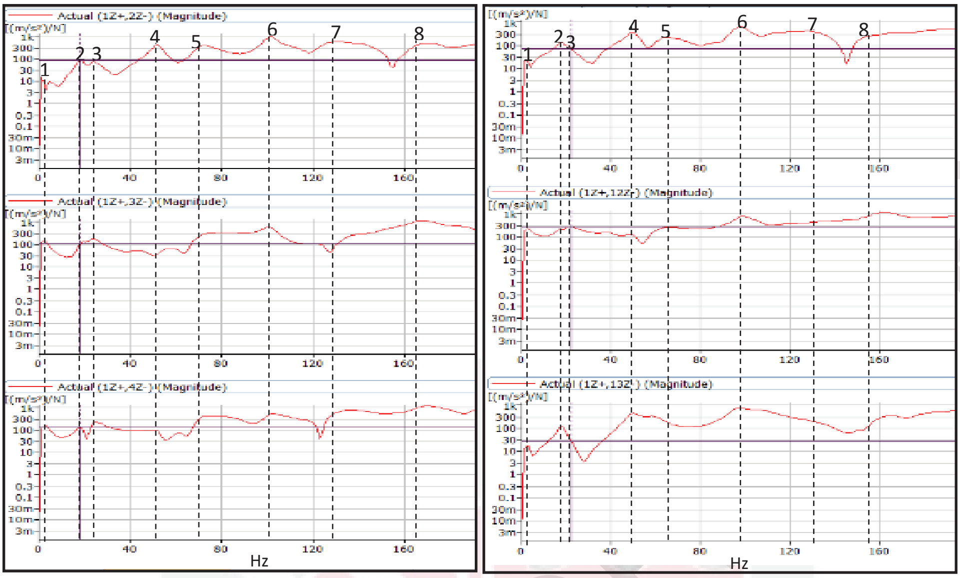


Appendix B1.2. FRF plot of L2L with SMA wire at mid (a) Inactive SMA wire (b) Activated SMA wire



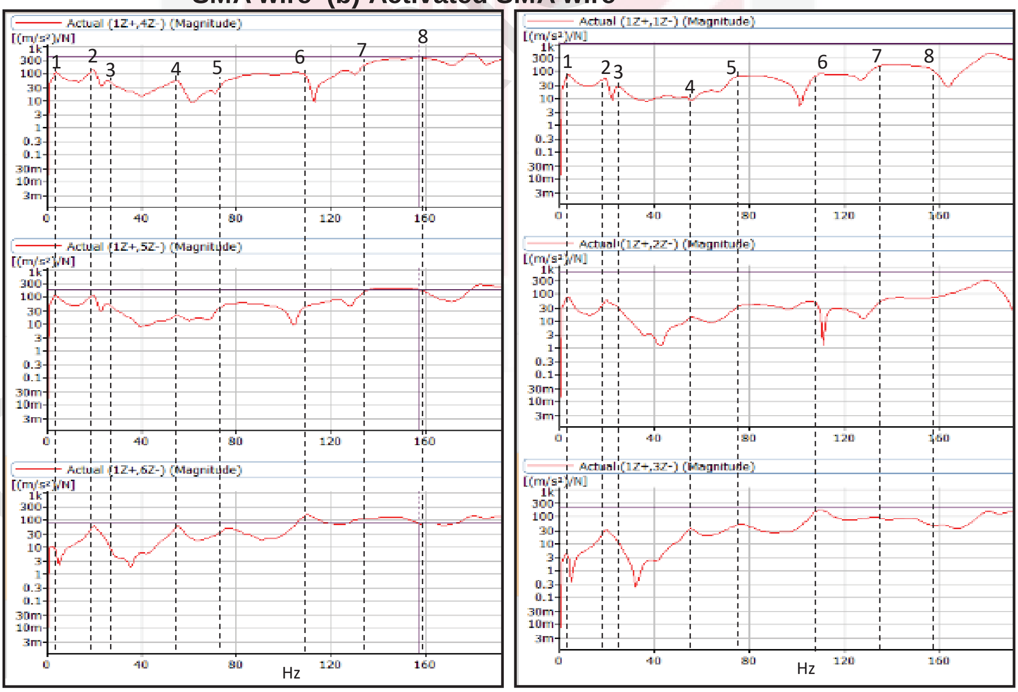
a b

Appendix B1.3. FRF plot of L2L with SMA wire at near to trailing edge (a) Inactive SMA wire (b) Activated SMA wire



a b

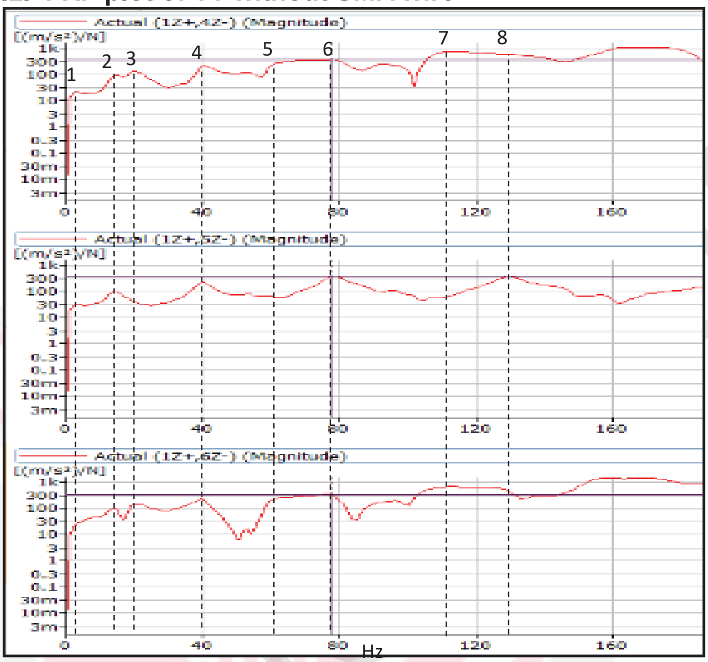
Appendix B1.4. FRF plot of L2L with SMA wire at leading edge (a) Inactive SMA wire (b) Activated SMA wire



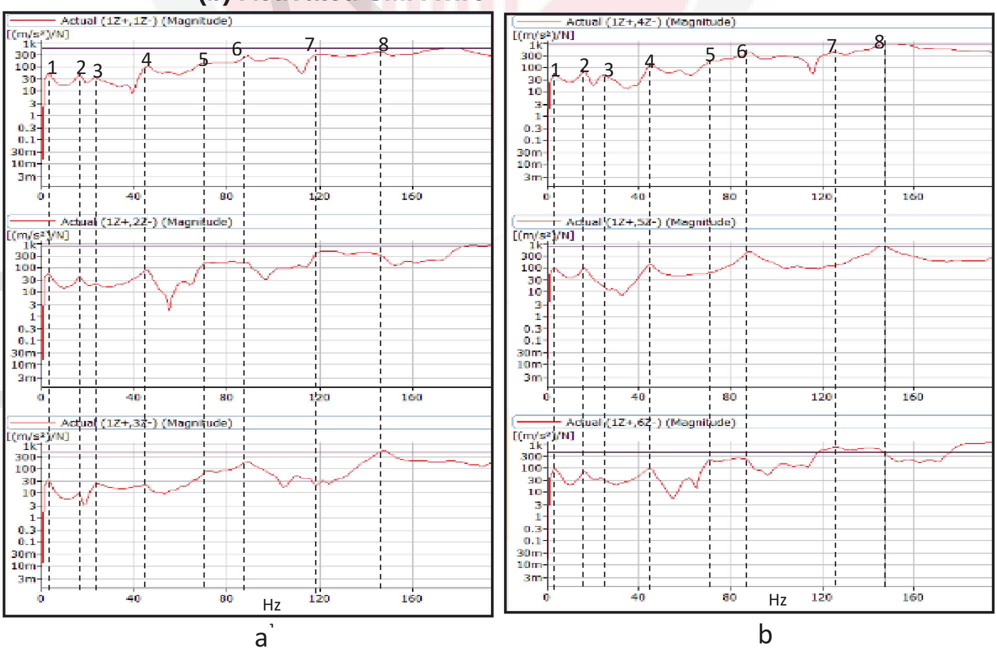
a b

Appendix B2

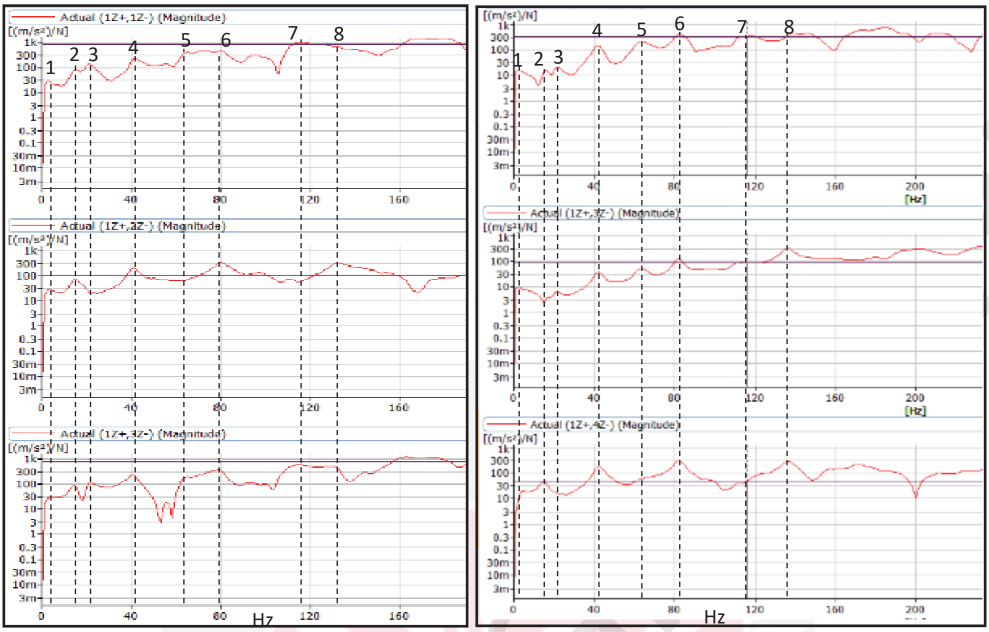
Appendix B2.1. FRF plot of TT without SMA wire



Appendix B2.2. FRF plot of TT with SMA wire at mid (a) Inactive SMA wire (b) Activated SMA wire

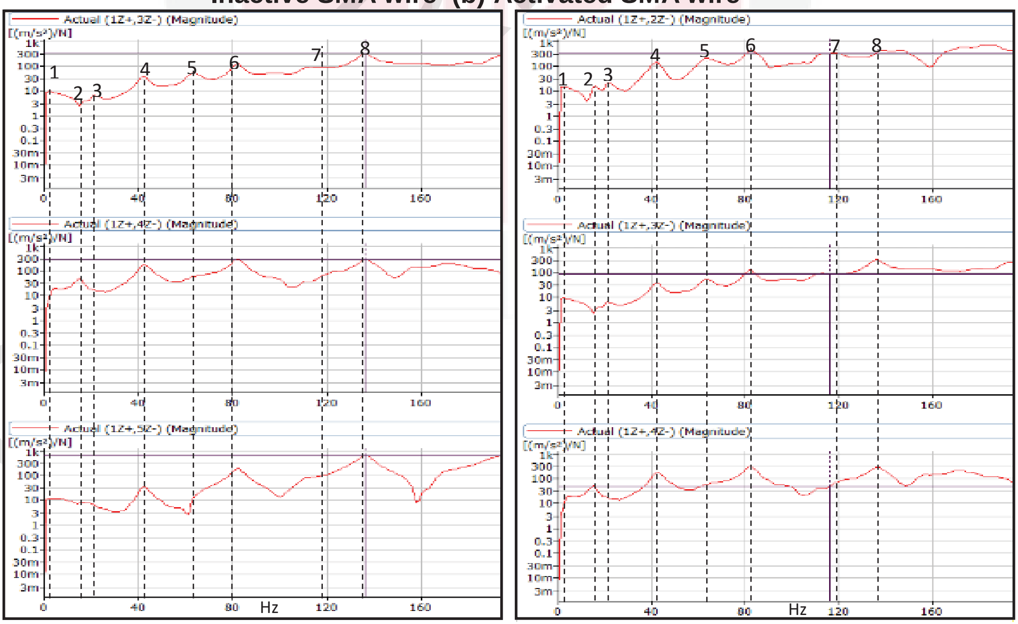


Appendix B2.3. FRF plot of TT with SMA wire at near to trailing edge (a) Inactive SMA wire (b) Activated SMA wire



a b

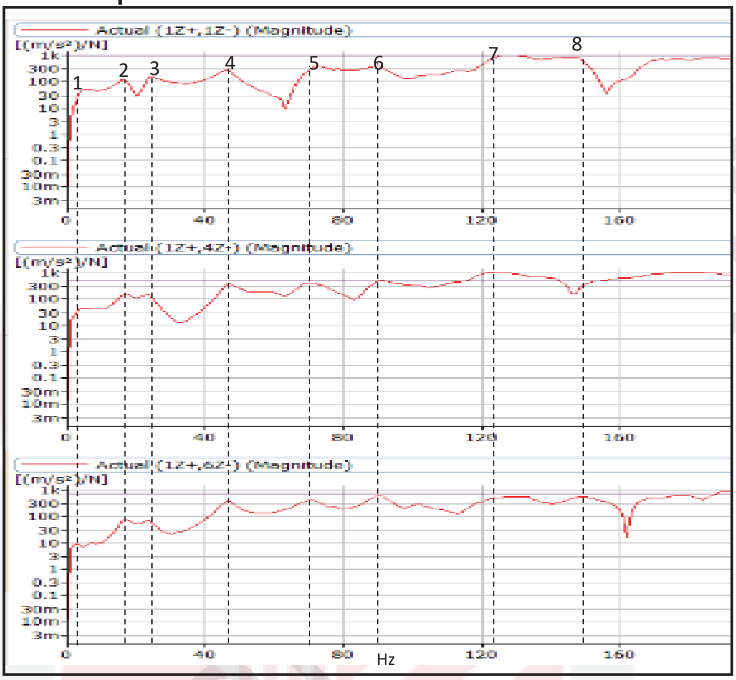
Appendix B2.4. FRF plot of TT with SMA wire at near to leading edge (a) Inactive SMA wire (b) Activated SMA wire



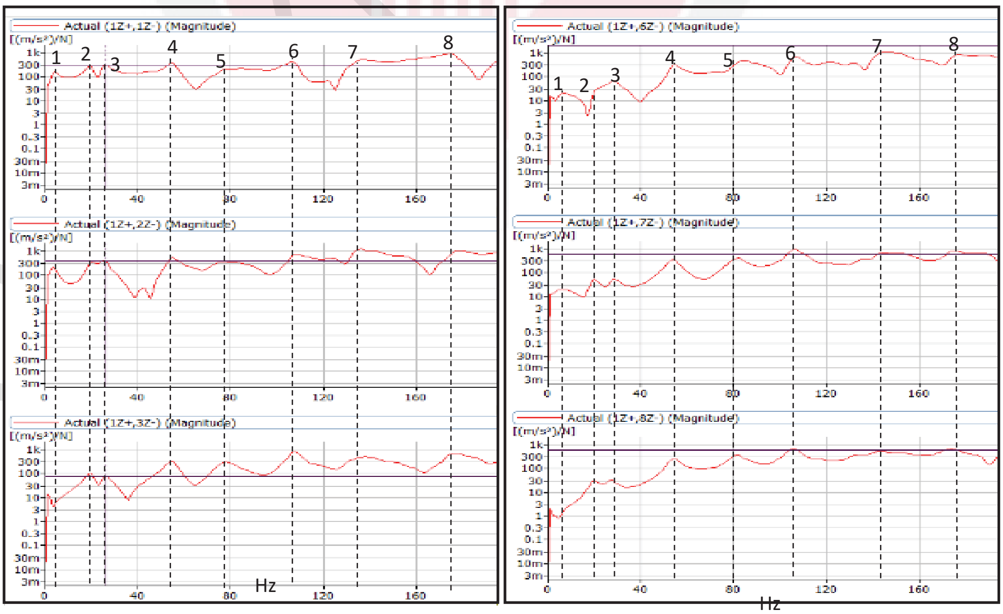
a b

Appendix B3

Appendix B3.1. FRF plot of MF without SMA wire

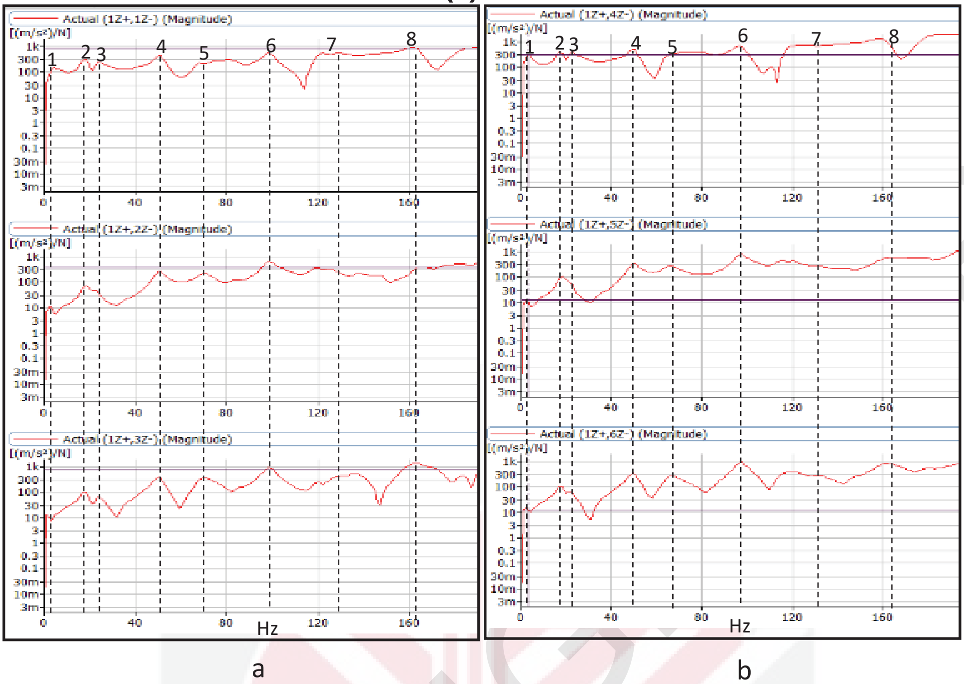


Appendix B3.2. FRF plot of MF with SMA wire at mid (a) Inactive SMA (b) Active SMA

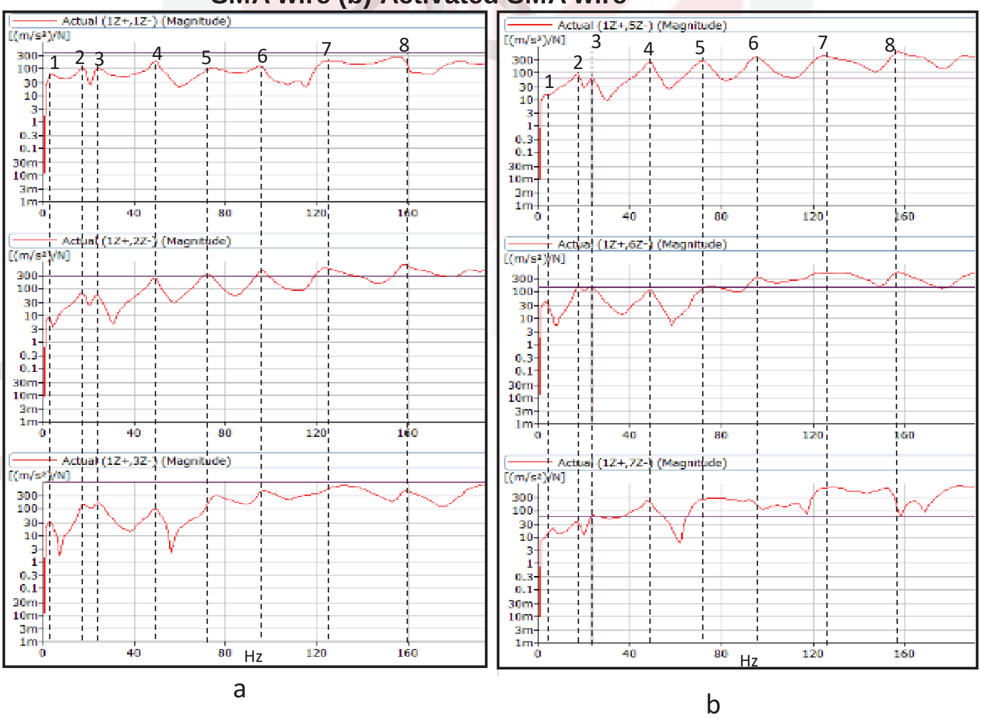


a b

Appendix B3.3. FRF plot of MF with SMA wire at near to trailing edge (a) Inactive SMA wire (b) Activated SMA wire



Appendix B3.4. FRF plot of MF with SMA wire at leading edge (a) Inactive SMA wire (b) Activated SMA wire



Appendix C1

Appendix C1. Calculations of bending moments of 3D woven L2L with inactive and activated SMA wire at mid

i) 3D woven L2L with inactive SMA wire at mid:

Length of the cantilevered composite plate=L =0.3 m,

Young's Modulus of 3D woven L2L with inactive SMA wire (calculated in section 4.2.3)= E=15.78 GPa

I= $bh^3/12$= 1.43* 10^{-12} m^4,

The aerodynamic loading is mainly depend on pressure of airflow and it is mainly responsible for bending of plate. Weight of the plate and other factors are neglected as these are same for inactive and activated SMA wire. So the load distributed to the plate is w1= *P*L.*

The Dynamic pressure of the airflow= $P = \frac{1}{2}\rho_{air}U^2$

Speed of air for maximum deflection of plate before flutter phenomenon is U(From Figure 4.22(b))= 5.98 m/sec

Density of the air= ρ=1.225 kg/m^3.

The Dynamic pressure of the airflow = $P = \frac{1}{2}\rho_{air}U^2$ =21.90 N/m^2

And the load distributed to the plate is w_1= *P*L* =6.57 N/m.

The bending moment at the tip of the cantilevered plate with inactive SMA wire (Equation 3.7)$M_1 = -\frac{w_1L^2}{6}$ = - 0.0986 Nm

The negative sign of the moment shows that the bending of the plate is in the downward direction.

The maximum deflection of the tip of the plate calculated(Equation 3.8) =$d_1 = \frac{w_1L^4}{30EI}$ = 0.0786m

ii) 3D woven L2L with activated SMA wire:

Young's Modulus of 3D woven L2L with activated SMA wire (section 4.2.3)= E=21.29 GPa

$I= bh^3/12= 1.43* 10^{-12} m^4$

Maximum deflection of the tip of the plate calculated from strain (Equation 3.9),

$d = \frac{2L^3}{3hx}(\varepsilon)$ =0.0789 m

Speed of air before flutter phenomenon for maximum deflection of the plate is

U(From Figure 4.22(c))=5.40 m/sec

Density of air is ρ=1.225 kg/m^3,

The Dynamic pressure of the airflow = $P = \frac{1}{2}\rho_{air}U^2$ =17.86 N/m^2

The load distributed to the plate due to airflow is $w_1= P*L$ =*5.358 N/m*.

'w_2' is calculated by rearranging equation Equation 3.13 ($d = \frac{w_1L^4}{30EI} + \frac{11w_2L^4}{120EI}$)

and putting values of d, w_1, L, E, and I.

w_2=1.286 N/m.

Now Bending moment at the tip of the plate with activated SMA wire(Equation 3.12) $= M = \frac{w_1L^2}{6} + \frac{w_2L^2}{3}$ = 0.1187 Nm.

So the bending moment of the plate with activated SMA wire is 20.39 % higher than the bending moment of the plate without activating the SMA wire.

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Danish Mahmood Baitab was born on 1st September, 1988 in Rawalakot, District Poonch, Azad Jammu and Kashmir, Pakistan. After completing his higher secondary education, he went to National Textile University Faisalabad, Pakistan. He completed his Bachelor's degree in "Textile Engineering" specialization of "Fabric Manufacturing" in 2012. He did his Master's degree in "Advanced Materials Engineering in 2015 from National Textile University Faisalabad, Pakistan. He joined National Textile University as a Lecturer in November 2012 and served five years. He was awarded a foreign scholarship by Higher Education Commission, Islamabad, Pakistan for PhD studies in 2017. Pursuing this, he took admission in the Department of Aerospace Engineering, University Putra Malaysia under the supervision of Associate Professor Dr. Dayang Laila Abang Abdul Majid, Dr. Ermira Junita Abdullah and Dr. Mohd Faisal Abdul Hamid.

LIST OF PUBLICATIONS

Baitab, D.M., Majid, D. L. A., Abdullah, E. J., & Hamid, M. F. A. (2018). A review of techniques for embedding shape memory alloy (SMA) wires in smart woven composites. *International Journal of Engineering and Technology*, *7*(4), 129-136.

Baitab, D.M., Majid, D. L. A., Abdullah, E. J., & Hamid, M. F. A. (2020). Improving the stiffness of multilayer 3D woven composites by the integration of shape memory alloys (SMAs) into structures. *The Journal of The Textile Institute*, *111*(9), 1371–1379.

Baitab, D.M., Majid, D. L. A, Abdullah, E. J., & Hamid, M. F. A. (2020). Tensile behavior of multilayer 3D smart woven composites embedded with shape memory alloy (SMA) wires. *Journal of Materials Research and Technology*, *9*(5), 10876–10885.

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