DESIGN AND DEVELOPMENT OF ARTIFICIAL NEURAL NETWORK MODEL FOR LIQUID PRESSURIZED SYSTEM BASED ON GLASS FIBRE REINFORCED EPOXY (GRE) COMPOSITE PIPE

by

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS
2018

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Date of Birth	:	16 JUNE 1989
Academic Session	:	2013-2018

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ACKNOWLEDGMENT

This research work was conducted at School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP) at Perlis, Malaysia. I would like to acknowledge my sponsors, Ministry of Higher Education Malaysia (MOHE) for providing the financial support under the MyBrain15 program.

First and foremost, I would like to thank my supervisor Associate Professor Dr Mohd Shukry Bin Abdul, Dr Azuwir Mohd Nor and Professor Sazali Bin Yaacob for the guidance and continuous support throughout the whole research. Their tolerance, wisdom, patience and expert views have made this project successful. There is no more I could ask from such gracious and friendly supervisors.

I would also like to take this opportunity to thank all staff and lecturers at the School of Mechatronic Engineering in UniMAP for their kind and needful assistance, encouragement and support during my research work.

Last but not least, I would also like to thank all my friends who were willing to share their knowledge and spend their precious time in discussing and solving problems that occured. And most importantly, the support and the constant encouragement from my family are the most precious in helping me to complete the research.

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
ASTM	American Society for Testing and Materials
CNC	Computer Numerical Control
cRIO	Compact Rio
DAQ	Data Acquisition
FPF	First Ply Failure
GFRP	Glass Fibre Reinforced Plastic
GRE	Glass Reinforced Epoxy
GUI	Graphic User Interface
ISO	International Organization for Standardization
MOHE	Ministry of Higher Education
NC	Normally Closed
NI	National Instruments
NO	Normally Open
OSHA	Occupational Safety and Health Administration
RMS	Root Mean Square
SIRIM	Standard and Industrial Research Institute of Malaysia
TPC	Touch Panel Controller
UEWS	Ultimate Elastic Wall Stress

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LIST OF SYMBOLS

E	Elastic modulus
G	Shear modulus
v	Poisson ratio
ρ	Density
σ_{axial}/σ_A	Axial stress
σ_{hoop}/σ_H	Hoop stress
σ_{ax}	Axial strain
σ_{hp}	Hoop strain
E_{axial}	Modulus of elasticity in axial
E_{hoop}	Modulus of elasticity in hoop
θ	Winding angle
E_1	Longitudinal modulus of the ply
E_2	Transverse modulus of the ply
V_f	Volume fraction of fibre
V_m	Volume fraction of matrices
v_f	Poisson ratio of fibre
v_m	Poisson ratio of matrix
E_f	Modulus of elasticity for fibre
E_m	Modulus of elasticity for matrices
G_f	Shear modulus of fibre
G_m	Shear modulus of matrices
E_{ax}	Axial modulus
E_{hp}	Hoop modulus
E_f	Modulus of elasticity (epoxy)
E_m	Modulus of elasticity (glass)
V_e	Volume fraction (epoxy)
V_g	Volume fraction (glass)
G_e	Shear modulus (epoxy)
G_g	Shear modulus (glass)

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REKA BENTUK DAN PEMBANGUNAN RANGKAIAN NEURAL PERTUDUHAN UNTUK SISTEM TEKANAN CECAIR PADA BERTETULANG GENTIAN KACA EPOKSI (GRE) PAIP KOMPOSIT

ABSTRAK

Dengan pertumbuhan pesat sains dan teknologi, paip komposit gentian kaca epoksi (GRE) paip telah menjadi sebahagian daripada elemen kejuruteraan yang penting dalam bidang kejuruteraan. Oleh itu, program pemantauan telah memainkan peranan penting dalam memastikan prestasi GRE pipe telah mencapai kualiti yang tertentu untuk digunakan. Berdasarkan ujian kelayakan ISO 14692, proses pengujian memerlukan jangka masa dan kos yang sangat banyak bagi memastikan kualiti komposit yang baru. Dengan bantuan daripada pemodelan matematik, prestasi paip komposit boleh diramalkan untuk mengurangkan ralat semasa mereka bentuk paip. Dengan itu, penyelidikan ini adalah bertujuan untuk memodelkan prestasi paip komposit GRE dan mengenalpasti titik kegagalan helaian pertama paip. Pertama sekali, model rangkaian saraf buatan (ANN) telah dibangunkan untuk meramalkan permulaan kegagalan paip komposit yang diperkuat oleh serat kaca. Pengembangan model ANN menggunakan data input yang merupakan modulus keanjalan (paksi), modulus keanjalan (gelung), pecahan isipadu, diameter, ketebalan, sudut penggulungan paip, nisbah ujian dan tekanan dan data output indikator kegagalan helaian pertama data eksperimen dari penyelidikan terdahulu. Data yang diperoleh kemudian menjalani proses "smoothing" dan klasifikasi untuk meningkatkan ketepatan model yang dibangunkan. Dalam proses "smoothing", data ditapis menggunakan algoritma pelicinan untuk menghapuskan data bunyi yang tidak perlu mengikut proses klasifikasi yang dikategorikan, diiktiraf dan dibezakan data dari populasi yang diketahui. Selepas pra-proses, data akan digunakan untuk proses latihan model. Dalam proses itu, parameter latihan rangkaian neural perlu ditetapkan. Parameter ini akan menentukan bilangan neuron dan bilangan lapisan neuron. Dalam perbangunan model, ketepatan purata model dikira berdasarkan sepuluh percubaan. Dengan itu, model ketepatan tertinggi yang diperolehi akan digunakan untuk meramalkan kegagalan pada paip komposit GRE. Rig ujian tekanan mudah alih juga dibangunkan berdasarkan protokol ujian monotonik / kitaran yang serupa dengan prosedur yang dijelaskan dalam piawaian ASTM D2992. Rig ujian berfungsi sebagai platform untuk mendapatkan data eksperimen untuk prosedur pengesahan model. Proses pengesahan pula akan dilakukan untuk meningkatkan kebolehpercayaan model ANN yang diperolehi. Proses pengesahan model akan dijalankan menggunakan beberapa data dari tempat lain yang tidak termasuk dalam data proses latihan. Oleh itu, model yang dibangunkan dijangka meramalkan kegagalan pertama di dalam komposit paip dibawah pelbagai nisbah tegangan biaxial. Dari hasilnya, struktur model tiga lapisan ANN telah dipilih dimana ketepatannya adalah diantara 95%-99.66%. Dari proses pengesahan model, perbandingan eksperimen yang berbeza telah dijalankan untuk mengesakan ketepatan paip GRE, ketepatan yang diperolehi adalah dalam lingkungan 77%-97%. Untuk ujian pengesahan dengan menggunakan ujian pencarian, persetujuan yang baik telah diramalkan dengan variasi kurang daripada 30%. Dari semua hasil, ini telah menunjukkan bahawa model ANN boleh diperluaskan untuk menghasilkan ramalan yang berguna berkaitan permulaan

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kegagalan dalam paip komposit di bawah pelbagai keadaan tekanan. Ini boleh digunakan sebagai kaedah untuk penarafan rating komposit paip untuk proses pemantauan mengikut piawaian ASTM.

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ABSTRACT

With the rapid growth of science and technology, glass fibre reinforced epoxy (GRE) composite pipe has become part of the vital engineering elements in the engineering field. Therefore, qualification program plays an important role to ensure that the performance of the GRE pipe has achieved a reliable standard with excellent quality. Conventional test procedure which refers to ISO 14692 qualification test based on the regression analysis requires typically extensive amounts of time and cost to identify the performance of the new composite pipe. With the aid of mathematical modelling, the performance of the composite pipe can be predicted where this can reduce errors when designing the pipe. This research aims to model the performance of the GRE composite pipes and thus, identify the pipe's first ply failure (FPF). First of all, an artificial neural network (ANN) model was developed to predict the onset of failure of GRE composite pipes. The ANN model was developed using input data namely, modulus of elasticity (axial), modulus of elasticity (hoop), volume fraction, diameter, thickness, pipe winding angle, stress ratio and pressure and the output data from the first-ply failure indicator of experimental data from previous research. The data obtained then underwent the smoothing and classification process to improve the accuracy of the model developed. In the smoothing process, the data was filtered using a smoothing algorithm to remove the unnecessary noise data followed by the classification process which categorised, recognised and differentiated the data from the known population. After the pre-processing, the data was used for the model training process. In the process, neural network training parameters needed to be decided. The parameter decided the number of neurons and the number of layers. In the model development, the mean accuracy of the model was calculated based on ten trials. By analysis and various trials, the highest accuracy model obtained would be used to predict the first-ply failure of the GRE composite pipe. A portable automated pressure test rig was also developed based on the monotonic/cyclic test protocol similar to the procedure elucidated in ASTM D2992 standard. The test rig served as a platform to obtain the experimental data for another model verification procedures. The validation process, on the other hand, was conducted to strengthen the reliability of the ANN model obtained. The validation process of the model was conducted using some other finding which was not included in the training process data. Therefore, the developed model was expected to predict the first-ply failure within the pipe composite laminated under various biaxial stress ratios. From the result, the three-layer ANN model structure was chosen where the means accuracy achieved was within 95%-99.66%. From the model verification process, the pure hydrostatic experimental comparison and the five different stress ratios test for ±55° GRE pipe accuracy was in the range of 77%-97%. For the validation test with experimental findings, a good agreement with the model's predictions was achieved, with less than 30% variation. From the results, it has suggested that the ANN model can be extended to yield useful predictions of the onset of failure in

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composite pipes under a range of stress conditions. This can be utilised as an internal means for pipe rating prior to the required standard of the ASTM qualification process.

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CHAPTER 1 : INTRODUCTION

1.1 Introduction/Background history

The composite material has become conventional materials which are intensively replacing metallic pipes. Most of the industries especially the petroleum industries are demanding for components which have high production rates and stricter occupational safety and health administration (OSHA) regulation. From the last decade, the quality and the capabilities of resin, fibre and fabrication equipment and processes allow a lot of the metal usage were converted to composites material (Spencer, 1998). Eventually, the composite system must offer superior mechanical properties such as high specific stiffness, high specific strength, corrosion resistance and fatigue resistance (Hull & Clyne, 2003). The glass fibre reinforced epoxy (GRE) piping system is often utilised in most of the application where the pipe can withstand competitive services, ambient and harsh environmental conditions. Due to the above advantages, the demand for the pipe to sustain high pressure, impact, rough handling and harsh environmental conditions such as corrosion and high temperature, the material was changed to composites as a solution to the weight and durability problems to meet the design goals.

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While engineers are turning to the advanced materials to meet the strict requirements, the composite material is chosen as a solution. GRE composite is one of the most widely used glass reinforced plastics which is capable of meeting a wide variety of end product requirements including fluid transport requirement. It has been extensively used in marine, building and also automotive industries. GRE composite is also customarily designed into pipes to withstand high pressures. Due to their lightweight and thin-walled structure, it provides a secure method of transportation and handling resulting to a lower installation cost (Frost, 1999). The corrosion resistance of the pipe properties is also one of the issues that leads to the extensive uses of the pipe due to highly corrosive fluid transportation (Gibson & Arun, 2016). The increase in the usage of this material has forced researchers to test the design limitations in term of its performance as the composite pipe is expected to serve for 50 to 100 years of services under the ground or sea.

Due to their long-term lifespan of services, the standard qualification of the GRE pipes has to be done despite it being highly expensive and time-consuming to achieve. Therefore, numbers of alternative solutions in the different possible tests can be achieved to predict the performance of the composite pipes. The tests such as flexural tests, ultimate-elastic wall stress (UEWS) tests and interlaminar shear stress (ILSS) tests are a few of the typical examples that are used for internal qualification procedures. The ultimate elastic wall stress (UEWS) test was first investigated by a Shell researcher in 1968 (Schwencke, H. F., 1968). However, there have only been limited studies made for the UEWS tests in the procedures. The UEWS tests involve typically in the application of cyclic pressure of hydrostatic tests at an increasing pressure level.

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Since the standard UEWS tests conducted require a physical pressurised test rig to perform, mathematical modelling has also become an alternative solution for an early stage prediction to reduce unwanted mistake. Moreover, the mathematical modelling is an alternative method which can be used as a simulation tool before any construction of the physical test. Examples of Tsai-Wu, Hashin criteria, Chang criteria and Puck criteria are some of the mathematical analysis that have been commonly used based on the required researches (Paris, 2001). Hence, derivation of a mathematical model using a more advanced method can be relatively new to the composite modelling.

System identification is a method which uses input and output data of the system to construct a mathematical modelling (Deng, 2009). This method has eliminated the difficulties of the needs for understanding the fundamental theory for the system. In recent years, as a constant development of the system identification technology, various methods have emerged to obtain better identification model. Methods like least square method, gradient correction methods are some of the methods which are commonly used nowadays. There are also some advanced methods in system identification such as neural network, fuzzy logic and genetic algorithm. By comparison, a suitable method to approach the system can be implemented.

The improved technology of the computation power has opened the opportunity in the research on the advance system identification method. This has become a new alternative field to be explored for those who are interested in producing a mathematical model. By using the neural network modelling method, a mathematical model can be developed. Therefore, a system can be easily predicted by using the mathematical model produced.

This research mainly focuses on the design and development of the mathematical model for the GRE composite pipe. The mathematical modelling developed was considered to predict the onset of failure if the first-ply failure (FPF) point. and thus, produce a biaxial failure envelope compatible with long-term tests in accordance with ASTM D2992 (D2992-06, 2006). Therefore, the artificial neural network (ANN)

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modelling method is a suitable method to be used in the research. First, experimental data were collected from previous research. The data were then processed as input parameters in the ANN training model. Afterwards, the results from the proposed model were compared with experimental tests conducted with the results of other research papers to analyse the accuracy of this model.

1.2 Problem statement

Composite pipe manufacturer must ensure that the pipe delivered is safe and can perform well within the requirements of the end users. Normally, the international standard ISO 14692 becomes the standard principle and working methods which deals with the qualification, system design and installation standard for the GRE piping systems. This has guided everyone in the industry to develop the similar understanding of the pipe. By using this method, it requires a test rig as well as a prolonged period of an experimental procedure to determine the long-term performance of the pipe through a short-term test. The main issue of this method is that at every new pipe design, a similar test will have to be repeated. This has become a waste in term of cost and time. To overcome these issues, failure prediction using the modelling approach is a solution that can be implemented as an internal qualification of the new pipe. Therefore, research on the development of a better model is essential to provide better suggestion to the researchers and manufacturer to select an appropriate design to meet their needs.

In the construction of the model, accuracy plays an essential role to determine its reliability. Most of the model are usually developed based on the micromechanics/energy method which involves complex mathematical equations. Those methods need time an

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in depth understanding of the micromechanical fundamentals which has made the modelling difficult and time-consuming. Since the computation power has seen some mass improvement in the last decade, neural network modelling techniques have been widely engaged in complex engineering problems. Such method enables the model to be generated through a collection of the existing qualification data. With the aid of computation power, a more complex and user-friendly model can be generated, and this may significantly reduce the difficulties of the model development.

This research aims to develop an engineering tool based on the ANN modelling for the manufacturer to identify the FPF point at the design stage. By providing the required input parameter, the model will have the ability to predict the behavior and the characteristics of the GRE pipes. By using the model, unnecessary pipe testing during the qualification processes of a new pipe's design can be avoided. In this research, details of the model developed is discussed in the following details.

A significant amount of research data on the performance of the GRE pipes will be collected at an early stage. After the data collection, the suitable data will be chosen. This data will undergo the smoothing process followed by the classification process that will be conducted. After the data processing, the data is then used in the construction of the model. After the model is constructed, verification and validation processes are used to determine the accuracy of the model.

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1.3 Objective

The primary objective of this work is to develop an advanced model based on the ANN modelling method. The model is expected to be able to predict the FPF of the composite pipe as part of internal qualification procedure before conducting the physical experimental test. For the research to achieve the objective, the following objectives of this research are focused:

Objective 1: To develop Artificial Neural Network (ANN) based model for the prediction of first ply failure (FPF) of glass fibre reinforced epoxy (GRE) composite pipes.

In the ANN model development, the model is produced based on the input parameters. Therefore, the reliability and accuracy of the data are taken into account in the early stage to ensure the accuracy of the model produced. In this stage, data is pre-processed where most of the noise is removed where a clean data is ready to be used in the model training stages.

Objective 2: To conduct the pressure test and thus, determine the first ply failure (FPF) point of the GRE composite pipes experimentally.

A pressurized test rig is developed where various experimental works are conducted to determine the FPF point experimentally. The main purpose of the experimental result is to compare with the constructed ANN model.

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Objective 3: To verify and validate the accuracy of the ANN model developed for FPF predictions.

Verification and validation are vital steps to ensure that the chosen model that represents the GRE composite pipe is the best ANN model. The model will undergo some verification tests from the result of the test rig and the validation tests from some other results of previous researchers.

1.4 Scope of research

The scope of this research is confined to the design and the development of a model-based identifier for the determination of the performance of the composite pipes. Therefore, the discussion in this thesis is focused on the modelling of the GRE composite pipe where its performance is identified by means of ANN modelling.

It is to be highlighted that the test protocol and the classifications of the model are conducted on GRE for a limited range configuration composite pipe. Thus, the FPF determination reports only works for glass fibre/epoxy which has the configurations of; volume fraction 0.5-0.66, winding angles of 45°-63°, the diameter of 100-200 mm, and thickness of 3-6 mm where the parameter chosen based on the standardize configuration of the composite pipe which generally found in the field. The model predicts the FPF within the five stress ratios range from pure axial (0H:1A) to pure hoop (1H:0A). Thus, it is paramount to state that the developed model suits only for a specific reinforcement material and parameter configurations. Different materials and configurations, on the

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