Failure prediction of ±55° glass/epoxy composite pipes using system identification modelling

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Abstract: Black-box modelling using system identification method to predict the performance of glass fibre reinforced epoxy (GRE) composite pipe under multiaxial loading stress ratio is presented. In this study, both linear and nonlinear models were derived namely; linear time-invariant parametric model and artificial neural network model. The models derived are to approximate the pure hydrostatic loading performance using GRE pipes with winding angles of ±55°. Three different linear model structures were derived, and the best fit model achieved at 96.64% of best fit. On the other hand, the Artificial Neural Network (ANN) modelling showed better accuracy with the best fit of 99.82%. Finally, the point of failure at which first damage takes place predicted by the models derived was validated using experimental data.

1. Introduction

Glass fibre reinforced epoxy (GRE) composite pipes possess unique characteristic of high strength, high stiffness, light weight and corrosion resistance. It has been widely used in oil and gas industries as an alternative to conventional steel pipes [1]. The qualification of GRE composites pipe is conducted through international standard ASTM D2992 [2] in order to ensure its quality and safety. Based on the standard, GRE composite pipe has to withstand a minimum life span service of 20-50 years. This requirement has become a primary design requirement for quality control. To meet these design requirement, a full-scale test of GRE pipes under long-term hydrostatic pressure loading test up to 10,000 hours was established [3]. This quality testing method required a duration of the testing up to one year or more, which will be an increased cost and time for industries. Therefore, to ensure smooth qualifying procedure of the GFE composite pipes without wasting unnecessary cost and time, pre-qualifying modelling is essential. Efficient modelling can significantly provide a faster and cheaper solution to predict the performance of the composite pipe before the actual qualifying procedure [6].

In recent research studies, several researchers have been working on a model to provide realistic predictions using the finite element modelling method. R.M. Guedes has studies on a stress-strain analysis of a cylindrical pipe subjected to a transverse load and large deflections [4]. The result
discusses the deformation theory on a high strength compared with the stiffness of the new material. The strain experimental measured and the final element analysis was performed to verify the phenomenon. A simple approach based on finite deformation theory was proposed and assessed.

Of late, Roham Fafiee et al. has also been looking into the theoretical modelling of fatigue phenomenon in composite pipes [5]. The modelling procedure has been divided into few phases to predicting the fatigue lifetime of the composite pipe. Their results suggested a good agreement between theoretically predicted fatigue lives of an industrial pipe with it long-term behaviour operation estimated test.

Besides that, Roham Fafiee and Ali Amini investigated on the modelling, and experimental evaluation of functional failure pressures in glass fibre reinforced polyester pipes [7]. A progressive modelling has been developed for the internal pressure wepage prediction which consists of failure evaluation, material degradation and stress analysis. The result shows that proper selection of the winding angle can overcome the adverse effect of fibre volume fraction.

Recently, most of the modelling methods are based on the theoretical analysis of the composite pipe. Hence, derivation of a mathematical model using identification method can be relativity new to the composite modelling. Based on the Li Fu research on the research survey of system identification method [8]. The study has mentioned that various types of identification technique which include system identification, neural network or fuzzy logic can be used to analyses complex model.

A.G Gibson and his team have conducted research on the qualification and lifetime modelling of fibreglass pipe [9]. They have been using the UEWS test on the cyclic fatigue test on fibreglass to model out the relationship between cyclic and static fatigue behaviour. By using the Miner’s law, it has found that it is effective in modelling the damage that can be related to the matrix cracking.

Abdul Majid and co-worker have modelled the strain responses of glass/epoxy pipes under various stress ratios. They managed to produce a model to predict the non-linear stress-strain response caused by the fatigue static and cyclic loading stress test. The prediction from the model is found to be in good agreement with the data from the multiaxial UEWS tests of ±55° filament wound GRE pipes [10]. They also have been working on the modelling of the general lifetime damage model for the GRE pipes which the model produced in a good agreement between the experimental data and the modelled developed [11]. Farhana et al. performed research on a new vibration based non-destructive testing for prediction glass fibre/matrix volume fraction in composites using a neural network model [12]. The neural network is used to determine the percentage of the fibre volume fraction. The results showed a good agreement with the standard destructive test for volume fraction determination which between the range of 90-98%.

The present research is intended to develop and validate mathematical models to predict the failure of the composite pipe. The model development will be based on system identification methods. The model will able to help to predict the behaviour of the composite pipe which will reduce the time and cost when developing new composite pipes.

2. Methodology

2.1. Glass Fibre Reinforced Epoxy Pipes (GRE)

The composite pipes with ±55° winding angle were fabricated through filament winding process at Industrial Research Institute of Malaysia (SIRIM), Kulim, Kedah. Standards E-glass fibres with a linear density of 1200 tex and DER-331 epoxy were used to create the fibre-matrix interface. The glass fibres were passing through a bath of epoxy resin maxis with hardener, and the wet fibre was wounded onto a mandrel of 100 mm in diameter. The pipe then cured around 2 hours in an oven. The specification of the GRE pipe is given in Table 1.
2.2 Experimental Procedure

A test rig was developed to undergo the cyclic loading test under multiple stress ratio loading tests. In this research, the focus of the experimental will only be on the pure hydrostatic (2H: 1A) loading test. The full schematic diagram of the automated pressure test rig for the pure hydrostatic setup is shown in Figure 1.

First, the pipe was installed with two custom design end-fittings with water filled inside it. The end fitting is sealed with O-rings to ensure that the leaks will not happen at the end fitting. To ensure no outward movement of the end fitting, serrated wedges placed in between the pipe wall to lock the movement. Before proceeding with the pressure testing, the composite pipe must be inspected to ensure that bubble trap inside the pipe is fully removed. Next, the pipe was placed in free-free conditions by hanging onto the test rig using lubricated rubber ring to reduce external disturbance. The strain gauge will be mounted onto the composite pipe using some special epoxy. The strain gauge was used to monitor the deformation takes place when the test is being conducted. The pipe fitting will be installed at the final stage depends on the test ratio needed.

The input signal is designed following the cyclic pressure loading which is controlled automatically using high-pressure solenoid valves. The input cyclic pressure was determined to be started with the pressure increment by 10% of the total expected failure pressure. The cycle of each pressure will last for ten cycles which consist of 60 seconds of the pressurised and non-pressurized condition. The test will be conducted until the leakage or weepage is observed from the outer surface of the pipe wall. The whole process was carried out automatically using the Ni-Compact RIO devices which including the increment of the input signal till the data collection. Visual inspection of the entire test will be done manually to determine the stopping time. All the data recorded from the experiment will be used to produce the model using identification method. A flow chart illustrated in Figure 2 presents the whole process of this research.

### Table 1. Composite pipes specifications.

| Specification               | Value |
|-----------------------------|-------|
| Winding Angle               | ±55°  |
| Average Length(mm)          | 1050  |
| Average Diameter(mm)        | 105   |
| Density(kg/m²)              | 1150  |
| Average wall thickness(mm)  | 4.34  |

**Figure 1.** Schematic Diagram of the Automated Pressure Test Rig.
2.3. Data Preparation
The modelling need the input and output data for construction, preparation of the data become an important role in determining the accuracy of the model. The data set from the experimental study is given in Table 2, which consist of the input pressure and the corresponding strain reading. A total number of 40562 data were prepared in each experiment. Before the modelling, a smoothing process will be conducted towards the data to remove unnecessary noise.

Table 2. Sample Data Collected.

| Pressure 1 (bar) | Pressure 2 (bar) | Hoop Strain | Axial Strain |
|-----------------|-----------------|-------------|--------------|
| 0.837809        | 0.614225        | 0.000029    | 0.000012     |
| 0.886995        | 0.659944        | 0.000028    | 0.000015     |
| 0.941061        | 0.715936        | 0.000033    | 0.000013     |
| 0.999558        | 0.770901        | 0.000042    | 0.000019     |
| 1.059467        | 0.830297        | 0.000042    | 0.000007     |
| 1.115973        | 0.893481        | 0.000039    | 0.000019     |

2.4. Identification Method
Identification modelling is a method which uses the input and the output of the system to construct a mathematical modelling. This approach has been developed and used by L.A Zadeh since 1962 [13]. There are several methods which can be employed in the identification modelling. For example, least square method, gradient correction process is among the few that are commonly used. Some advanced method such as neural network and fuzzy logic has slowly become a trend in the modelling world [14]. However, each different method consists of pros and cons of its usage. In this study, both linear and nonlinear model consist of system identification based method and artificial neuro network modelling will be used.
2.4.1. System identification
System identification is also known as parameter identification. In constructing the system identification, there are several parameter structures which were used which given in Table 3. The system identification modelling was built via MATLAB system identification toolbox (SIT) which consists of those structures. The ARX model stands for the autoregressive moving average model, and ARMAX is autoregressive moving average with exogenous term model.

| Table 3. Model Structures for Linear Model. |
|---------------------------------------------|
| **ARX MODEL** | \( A(z)y(t) = B(z)u(t-nk) + e(t) \) | (1) |
| **ARMAX MODEL** | \( A(z)y(t) = B(z)u(t-nk) + C(z)e(t) \) | (2) |
| **TRANSFER FUNCTION** | \( Y(s) = \frac{\text{num}(s)}{\text{den}(s)} u(s) + E(s) \) | (3) |

2.4.2. Artificial Neuron Network Modelling (ANN Modelling) (Nonlinear Model)
Artificial Neuron Network is the other powerful tools which have the ability to construct some complex model [19]. By using the mathematical structure which shown in Equation Error! Reference source not found., the construction of the AI model can be processed by using the input-output of the data.

\[
y_{\text{output}} = (\sum_{i=0}^{k} W_i \ast I_i)
\]

where \( y_{\text{output}} \) = value propagates to next layer
\( W \) = weight of the neuron
\( I \) = neuron value gain

3. Results and Discussion
3.1. Comparison of the Model Structure
For comparison purposes, all three linear model structures were analysed, and the 1st order mathematical models are tabulated in Table 4. Three models where produce and their accuracy according to the best fit are compared. According to the result, the ARX model achieved the best fit of 86.39% followed by the ARMAX with the best fit of 87.13%. Overall, the highest best fit produce by the system identification modelling is the transfer function structure model at 96.64%. The results show that ARMAX model has the better fit than ARX. This is due to the ARMAX model structure has included the properties of the error term which is lag inside the ARX model. For the ARX structure model, the noise entered directly into the structure parameter which introduced errors within the design model. Inside the ARMAX model, the noise is separated and resulted in the better model closer representation of the physical design.

Transfer function structure model are the model which using the Laplacian transform pole and zero. This method will produce a continues equation based on the S-plane model. On the other hand, the ARX and ARMAX model are using the linear time invariant model which produce model base on the Z-transform. Therefore, the model produces on the continues plane (S-plane) will obtain a better best fit result compare with a discrete model (Z-Transform). This is due to the discrete model normally will lose part of it data when the model is being digitalize.
The other factor which will impact on the accuracy of the model will be the decision of the number of order. The number of order will be best to describe as the power factor is a mathematical equation. Table 5 has shown the best fit that each model until 3rd order model. This is because most of the model can be achieved in this region. Moreover, the model will be too complex to handle if the number of order is too high. From Table 5, The 1st order model produced by transfer function will be chosen to represent the model. Although it has shown that the best fit is the 3rd order model produced by the transfer function structure, due to the small increment the 1st order structure will be used.

Table 5. Accuracy of the Model for different Pole and Zero.

| Pipe Winding Angle and Estimator | Best Fit (%) Hoop Strain | Best Fit (%) Axial Strain |
|----------------------------------|--------------------------|---------------------------|
| **Number Of Order (P/Z)**        |                          |                           |
| **55°**                          |                          |                           |
| ARX                              | 86.39                    | 66.07                     |
| ARMAX                            | 87.13                    | 67.12                     |
| Transfer Function                | 96.64                    | 86.1                      |

Figure 3 illustrates the nonlinear model structure which was generated to represent the system. From the figure, the ANN model structure consists of 1 layer with three neurons. The structure value for all weight and bias which represent the system model is shown in Figure 3. From the calculation using the system, the ANN Model has achieved the best fit of 99.82%.
3.2. Model Comparison

The developed mathematical model is expected to determine the onset of ply failure for the composite pipes. Figure 4 below shows the hoop strain versus pressure results for both; identification model and the experimental result. There were three plots presented; two were predictions from the system identification model and artificial neural network models and another is the experimental findings as reported by M.S. Abdul-Majid et al. [15]. The prediction from system identification model is computed using equation (5) while artificial neural network model was developed from the output obtained from the model structure shown in Figure 3

\[
F(x) = \frac{8.317 \times 10^{-5}S + 9.242 \times 10^{-9}}{S + 6.982 \times 10^{-5}}
\]

From Figure 4, the graph shows that the linear model and the non-linear model are able to predict the behavior of the system. But the transfer function model which is the linear model were only able to predict the behavior of the system up to the point where the crack happens. It has shown that the models are only good in predicting the linear region. Since the system which under testing will change its behavior to shows exponential like behavior, the ANN model has shown a much better performance in predicting the behavior of the system. Thus, the ANN model is better in modelling since it represents a nonlinear model structure.

By comparing both the linear and on-linear model, the onset of first ply failure is suspected of taking place when the stress-strain curve deviates from the linear responses and exceeds a defined threshold level as to suggest permanent deformation occurred within the ply structure. From Figure 4, it could be suggested that the model did show some agreement to a degree to the experimental data. The prediction from both models shows good prediction, particularly in the linear region. The predictions from system identification model start to show deviations from the straight linear relationship at roughly about 40 bars.
The results imply that the models provide a reasonable prediction of the onset first ply failure before functional failure such as weepage takes place albeit the variance in accuracy. The result seems to suggest that the system identification model has detected the damage by comparing with the ANN Model structure. This is because the system identification is a linear model compared to the ANN Model which is more robust. The ANN Model produced inclines to adapt the characteristic of the composite pipes thus indicates the non-linearity. Nonetheless, both models showed acceptable predictions of the onset of the damage for the GRE pipes when comparing together.

5. Conclusion
In conclusion, two different model types were developed to predict the onset of damage in the ply structure of GRE composite pipes, namely; linear time-invariant and ANN nonlinear models. The system identification based model was performed by using three different model structures, and the best fit the model achieved at 96.64% of best fit. On the other hand, the ANN modelling method produced the best fit of 99.82%. The models generated are then compared to the experimental data and presented in the hoop strain-stress (bar) plot. Both prediction models show reasonable agreement with experimental findings though with variance in accuracy levels. The results suggest that the models can be used as a preliminary/early procedure to predict the onset of damage in the GRE pipes before experimental means is applied.

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7. References
[1] S. N. Fitriah, M. S. Abdul Majid, M. J. M. Ridzuan, R. Daud, A. G. Gibson, and T. A. Assaleh, “Influence of hydrothermal ageing on the compressive behaviour of glass fibre/epoxy composite pipes,” Compos. Struct., vol. 159, pp. 350–360, 2017.
[2] “ASTM D2992-06. Standard test method for obtaining hydrostatic or pressure design basis for reinforced thermosetting resin pipe and fitting. American Society for Testing and Materials; 2006.”

[3] “ASTM D5365-06. Standard test method for long-term ring bending of fiberglass pipe. American Society for Testing and Materials; 2006.”

[4] R. M. Guedes, “Stress-strain analysis of a cylindrical pipe subjected to a transverse load and large deflections,” Compos. Struct., vol. 88, no. 2, pp. 188–194, 2009.

[5] R. Rafiee and F. Elasmi, “Theoretical modeling of fatigue phenomenon in composite pipes,” Compos. Struct., vol. 161, pp. 256–263, 2016.

[6] A. Hawa, M. S. Abdul Majid, M. Afendi, H. F. A. Marzuki, N. A. M. Amin, F. Mat, and A. G. Gibson, “Burst strength and impact behaviour of hydrothermally aged glass fibre/epoxy composite pipes,” Mater. Des., vol. 89, pp. 455–464, 2016.

[7] R. Rafiee and A. Amini, “Modeling and experimental evaluation of functional failure pressures in glass fiber reinforced polyester pipes,” Comput. Mater. Sci., vol. 96, no. PB, pp. 579–588, 2015.

[8] L. Fu and P. Li, “The Research Survey of System Identification Method,” 2013 5th Int. Conf. Intell. Human-Machine Syst. Cybern., pp. 397–401, 2013.

[9] A. G. Gibson, M. S. Abdul Majid, T. A. Assaleh, J. M. Hale, A. Fahrer, C. A. P. Rookus, and M. Hekman, “Qualification and lifetime modelling of fibreglass pipe,” Plast. Rubber Compos., vol. 40, no. 2, pp. 80–85, 2011.

[10] M. S. Abdul Majid, A. G. Gibson, M. Hekman, M. Afendi, and N. A. M. Amin, “Strain response and damage modelling of glass/epoxy pipes under various stress ratios,” Plast. Rubber Compos., vol. 43, no. January 2016, pp. 290–299, 2014.

[11] M. S. A. Majid, M. Afendi, R. Daud, N. a. M. Amin, A. Mohamad, E. M. Cheng, a. G. Gibson, and M. Hekman, “General Lifetime Damage Model for Glass Fibre Reinforced Epoxy (GRE) Composite Pipes under Multiaxial Loading,” Key Eng. Mater., vol. 594–595, no. January 2014, pp. 624–628, 2013.

[12] N. I. E. Farhana, M. S. Abdul Majid, M. P. Paulraj, E. Ahmadhilmi, M. N. Fakhzan, and A. G. Gibson, “A novel vibration based non-destructive testing for predicting glass fibre/matrix volume fraction in composites using a neural network model,” Compos. Struct., vol. 144, pp. 96–107, 2016.

[13] L. A. Zadeh, “From Circuit Theory to System Theory,” Proc. IRE, vol. 50, no. 5, pp. 856–865, 1962.

[14] A. J. Yi, M. S. A. Majid, A. M. N, and S. Yaacob, “Microcontroller-Based For System Identification Tools Using Least Square Method For Re Circuits,” J. Teknol., 2015.

[15] M.S. Abdul Majid, T.A. Assaleh, A.G. Gibson, J.M. Hale, A. Fahrer, C. A. P. Rookus, and M. Hekman, “Ultimate elastic wall stress (UEWS) test of glass fibre reinforced epoxy (GRE) pipe,” Compos. Part A Appl. Sci. Manuf., vol. 42, no. 10, pp. 1500–1508, Oct. 2011.