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Failure Prediction of Fiber Reinforced Polymer Pipes using FEA

Ahmed W. Abdel-Ghany, Iman Taha, Samy J. Ebeid

***Abstract*— Numerical study is done to predict the failure of fiber reinforced polymer pipes produced by filament winding when subjected to pure internal pressure. The analysis is done using the last ply failure technique for a four layered pipe oriented anti-symmetrically [±Ø°]$_2$. ANSYS Composite PrepPost (version 15) is used for analysis. Three different composites were examined in this study: E-glass fiber/epoxy, carbon fiber/epoxy and aramid fiber/epoxy. Numerical analysis was further validated through experimental data in case of E-glass fiber/epoxy composite. Comparison proves a good degree of correlation. The maximum burst pressure for the three types of material is realised at [±55°]$_2$ compared to a minimum pressure at [±0°]$_2$.**

***Index Terms*—Failure analysis, Filament winding, Finite element analysis, Polymer matrix composites.**

I. Introduction

Advanced composite materials are nowadays used to fabricate many structural parts in engineering applications due to their promising properties compared to other monolithic materials. Composite materials offer light weight at high strength, high stiffness, good fatigue resistance and good corrosion resistance [1]. Further, composites bring along the advantage of tailoring the material according to the needs of the end product [2].

Composite pipes can thus combine selective directional (anisotropic) properties to meet specific application needs. Filament winding is a process used to produce such composite pipes. The process, as schematically illustrates in Fig.1, is used to wrap resin-impregnated continuous fibers around a rotating mandrel that has the internal shape of the desired product [3, 4].

Design and analysis of composites should consider several aspects not limited to material properties, examination of production parameters, investigations of geometries and loading conditions. Burst pressure is an important parameter that must be well studied in case of pipes. This, and other properties will change by altering filament type, roving size, number of layers and winding angle (Ø), to mention a few of the affecting parameters. The winding angle is measured between the rotating axe and wrapped fiber, as indicated in Fig. 2.

Ahmed W. Abdel-Ghany, Design and Production Engineering Department, Ain Shams University/ Faculty of Engineering, Cairo, Egypt, +201119555036.

Iman Taha, Design and Production Engineering Department, Ain Shams University/ Faculty of Engineering, Cairo, Egypt, +201289369100.

Samy J. Ebeid, Design and Production Engineering Department, Ain Shams University/ Faculty of Engineering, Cairo, Egypt, +201223720125,

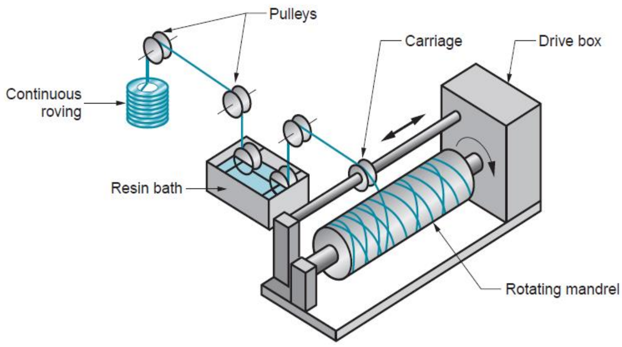


Fig. 1 - Common form of Filament winding process [5]

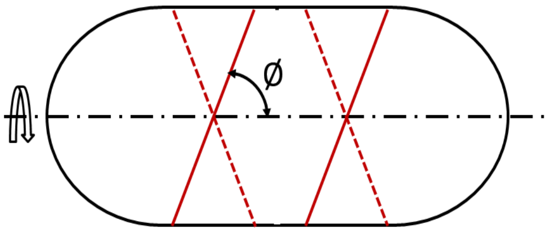


Fig. 2 - Winding pattern in filament winding

Literature reports analytical analysis for pipes subjected to pure internal pressure fulfilling a hoop to axial stress ratio of 2:1, and the optimum burst pressure was found to occur at a winding angle of 54.7° [6, 7]. Experimental results meet these theoretical findings [8-10]. Soden et al. experimentally investigated the failure stresses for ±55° filament wound glass fiber reinforced plastic tubes under biaxial loads. Bai et al. studied the mechanical behavior of ±55° filament-wound glass-fiber/epoxy-resin tubes from different aspects in a series of researches [11-13].

Finite Element Analysis (FEA) is considered a powerful tool to reduce the trials used to produce the required part. Last ply failure (LPF) is used as an assessment tool in FEA to determine the failure load for composite layers [14]. This theory implies that composite failure will occur when all layers fail. Each layer is investigated separately using FEA and the failure load can be individually determined for each layer.

The objective of this paper is building a Finite Element model to investigate the burst pressure of different composite pipes, at high accuracy. This model can be further used as a design tool to select the best parameters for optimum design prior to production.

II. Quadratic Failure Criterion

A quadratic criterion is the commonly used criterion for fiber-reinforced composites [15]. A quadratic criterion combines all stress or strain components into a general form that can be expressed as a second-degree polynomial for plane stresses as given by (1).

$$f = F_{11}\sigma_1^{\,2} + F_{22}\sigma_2^{\,2} + F_{66}\tau_{12}^{\,2} + 2F_{12}\sigma_1\sigma_2 + F_1\sigma_1 + F_2\sigma_2 \quad (1)$$

X_t and X_c denote the tensile and compressive strengths in the direction of fiber, Y_t and Y_c are the tensile and compressive strengths transverse to fiber direction and S is the shear strength in the same plane. The coefficients F_{11}, F_{22}, F_{66}, F_1, and F_2 present material strength in the principle material directions. These coefficients and F_{12} can be determined in various ways, based on the following theories.

A. *Tsai Wu failure criterion*

$$F_{11} = \frac{1}{X_t X_c}\ ,\ F_1 = \frac{1}{X_t} - \frac{1}{X_c}\ ,\ F_{22} = \frac{1}{Y_t Y_c}\ ,$$
$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}\ ,\ F_{66} = \frac{1}{S^2}\ , \quad (2)$$
$$2F_{12} = XY,\ default - 1$$

Therefore Tsai-Wu criterion can be written as:

$$f = \frac{\sigma_1^{\,2}}{X_t X_c} + \frac{\sigma_2^{\,2}}{Y_t Y_c} + \frac{\tau_{12}^{\,2}}{S^2} - \sigma_1\sigma_2$$
$$+ \left(\frac{1}{X_t} - \frac{1}{X_c}\right)\sigma_1 + \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)\sigma_2 \quad (3)$$

B. *Tsai Hill failure criterion:*

$$F_{11} = \frac{1}{X^2}\ ,\ F_1 = 0\ ,\ F_{22} = \frac{1}{Y^2}\ ,\ F_2 = 0\ ,$$
$$F_{12} = -\frac{1}{2X^2}\ ,\ F_{66} = \frac{1}{S^2} \quad (4)$$

X and Y are defined as follow:

$$\sigma_1 \geq 0 \rightarrow X = X_t \quad ; \quad \sigma_1 < 0 \rightarrow X = X_c$$
$$\sigma_2 \geq 0 \rightarrow Y = Y_t \quad ; \quad \sigma_2 < 0 \rightarrow Y = Y_c \quad (5)$$

Therefore Tsai-Hill criterion can be written as:

$$f = \left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 - \left(\frac{\sigma_1\sigma_2}{X^2}\right)^2 \quad (6)$$

C. *Hoffman failure criterion:*

$$F_{11} = \frac{1}{X_t X_c}\ ,\ F_1 = \frac{1}{X_t X_c}\ ,\ F_{22} = \frac{1}{Y_t Y_c}\ ,$$
$$F_2 = \frac{1}{Y_t Y_c}\ ,\ F_{12} = -\frac{1}{X_t X_c}\ ,\ F_{66} = \frac{1}{S^2} \quad (7)$$

Therefore Tsai-Hill criterion can be written as:

$$f = \left(\frac{\sigma_1^{\,2}}{X_t X_c}\right) + \left(\frac{\sigma_2^{\,2}}{Y_t Y_c}\right) + \left(\frac{\tau_{12}^{\,2}}{S^2}\right) - \frac{\sigma_1\sigma_2}{X_t X_c} + \frac{\sigma_1}{X_t X_c} + \frac{\sigma_2}{Y_t Y_c} \quad (8)$$

III. Finite Element Analysis

A. *Model building*

A mechanical model of the pipe is built in ANSYS Composite PrepPost (ACP) with the dimensions shown in Table 1 [8]. The geometry of the pipe is defined using shell geometry in the ACP. Quadratic shell element (SHELL281), as illustrated in Fig. 3 is selected for the analysis.

The mesh generated on the shell geometry is further shown in Fig. 4. To simulate the hydraulic burst failure test, fixed supports are applied at both pipe ends. Pressure is applied to the internal pipe wall, as schematically presented in Fig. 5.

Table 1: Dimensions of the pipe

Length of the pipe	400 mm
Internal diameter of pipe	100 mm
Wall thickness of pipe	1.6 mm
Approximate Thickness of each layer	0.4 mm

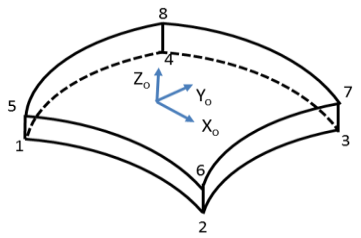


Fig. 3 - Shell element

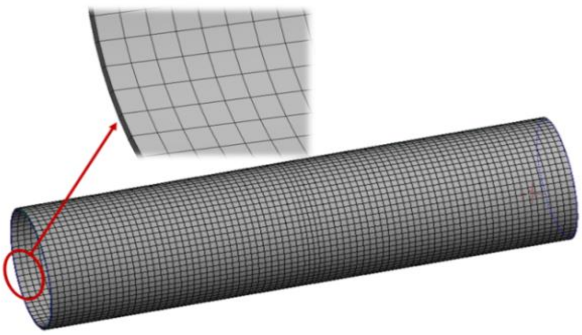


Fig. 4 - Generated shell element for a four layered pipe

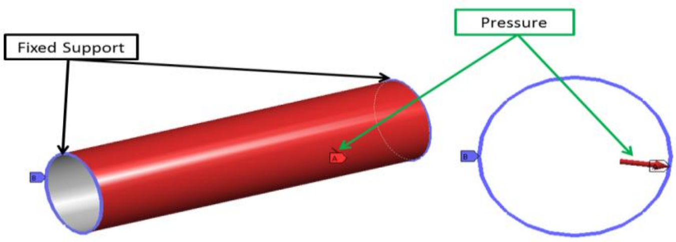


Fig. 5 - Loading conditions and constrains

E-glass fiber/epoxy material is defined in the model using the literature data summarized in Table 2 [8]. Four anti-symmetrical layers are applied to the geometry $[\pm Ø°]_2$. The default fiber direction (0° orientation) is defined parallel to the pipe axis, which is also the mandrel axis of rotation as well as the reference line from which the winding angle is measured (Fig. 6). Different winding angles are used for simulation: $[\pm 45°]_2$, $[\pm 55°]_2$, $[\pm 60°]_2$, $[\pm 75°]_2$ and $[\pm 90°]_2$, as indicated in Fig. 7.

Table 2: Properties of E-glass Fiber/Epoxy

Property		E-glass Fiber/Epoxy
Young's Modulus	E_x (GPa)	36.5
	$E_y = E_z$ (GPa)	15
Poisson's Ratio	$V_{xy} = V_{xz}$	0.24
	V_{yz}	0.22
Shear Modulus	$G_{xy} = G_{xz}$ (GPa)	6.35
	G_{yz} (GPa)	1.6
Tensile Strength	X_t (MPa)	1050
	$Y_t = Z_t$ (MPa)	43
Compression Strength	X_c (MPa)	-938
	$Y_c = Z_c$ (MPa)	-106
Shear Strength	$S_{xy} = S_{yz} = S_{xz}$ (MPa)	88

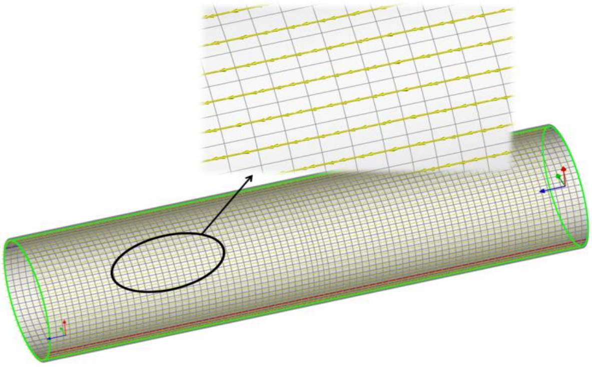
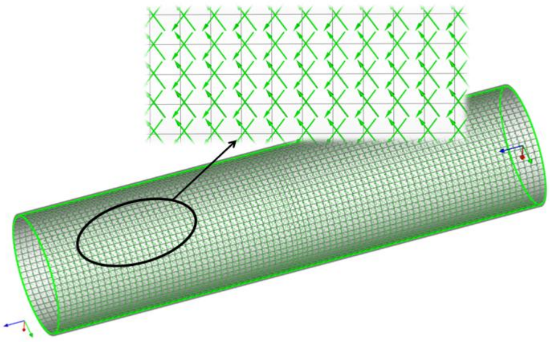


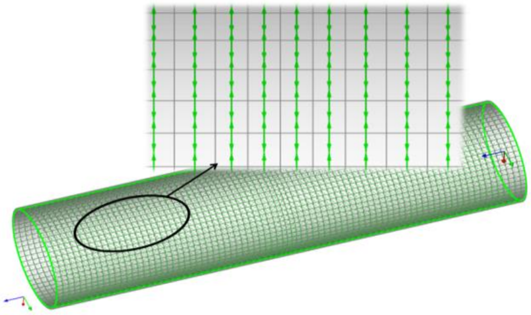
Fig. 6 - Reference direction for fibers

B. *Numerical analysis*

The element size directly affects FEA results. A coarse element will give the advantage of reduced solving time but with lack of accuracy, and vice versa for the fine elements. Using the concept of the LPF, the burst pressure will be determined for each individual ply. A randomly selected pressure value is applied as an initial load, where the Reserve Factor (RF) is determined for each ply individually. The Reserve Factor (RF) is used to determine the margin to failure, where the failure load is equal to the applied load multiplied by the RF. In other words, if RF is greater than one the applied load is low and needs to be increased to cause failure, and vice versa.



(a)



(b)

Fig. 7 - Fiber orientation for (a) $[\pm 55°]_2$ and (b) $[\pm 90°]_2$

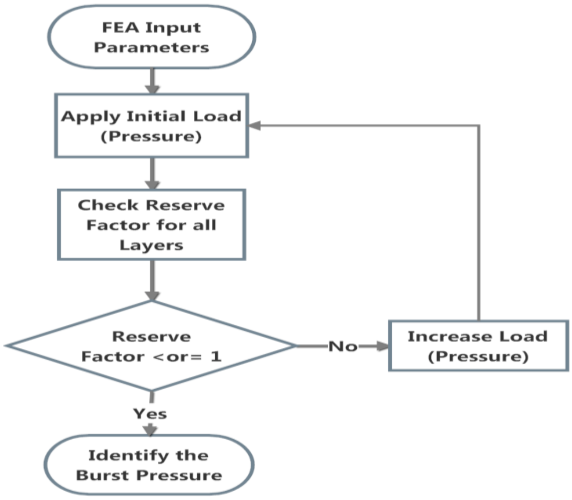


Fig. 8 - Flow chart for the Finite Element Analysis using Last Ply Failure

The failure pressure is then determined using (9), where $P_{failure}$ is the failure load and $P_{applied}$ is the applied load. This is equivalent to the minimum pressure required to cause a failure in all plies of the pipe (burst pressure).

$$P_{failure} = P_{applied} \times RF \qquad (9)$$

Hence, to apply LPF, all RF must be slightly less than or equal to one. Otherwise a higher value for pressure is selected and the test is run again until this condition is satisfied. The flow chart given in Fig. 8 shows the various stages of the analysis.

Several trials are conducted using the ACP Analysis to determine the optimum number and size of elements. The predicted burst pressure is compared to the experimental value known for an E-glass/epoxy pipe manufactured at 55° winding angle $[\pm 55°]_2$.

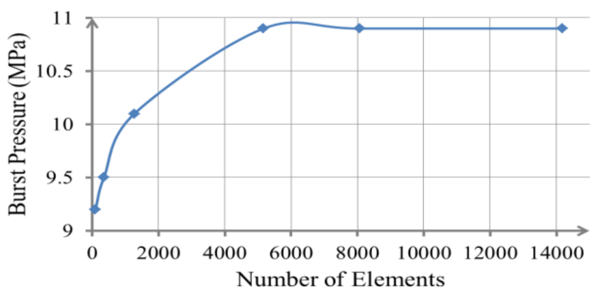


Fig. 9 – Burst Pressure vs. number of elements for pure internal pressure of E-glass/epoxy pipe with $[\pm 55°]_2$ winding angle

Fig. 9 presents the effect of element number on the predicted burst pressure. It can be observed that the burst pressure increases with increasing number of elements, up to an element number of about 5000, after which results start to stabilize at a constant pressure of 10.9 MPa. Based on these results, an element size of 5 mm (approximately 5200 elements) will be sufficient for predicting the burst pressure with an acceptable percent of error at a reasonable computational cost.

Finally the simulated results are compared to experimental values.

IV. Numerical Results

A. Model Verification

Three theories were used to compare numerical and experimental results, namely the Tsai-Wu, Tsai-Hill and Hoffman theories. Fig. (10-12) show the results of these analyses in contrast to the experimental data for a glass fiber/epoxy pipe produced by filament winding.

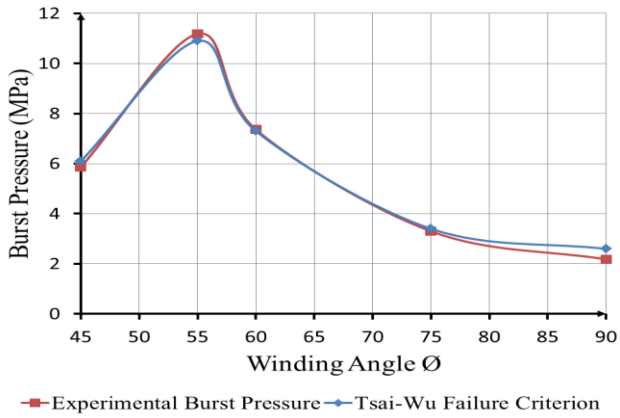


Fig. 10 - Comparative analysis between experimental results and Tsai-Wu failure criterion for $[\pm Ø°]_2$ E-glass fibers/epoxy orthotropic tubes

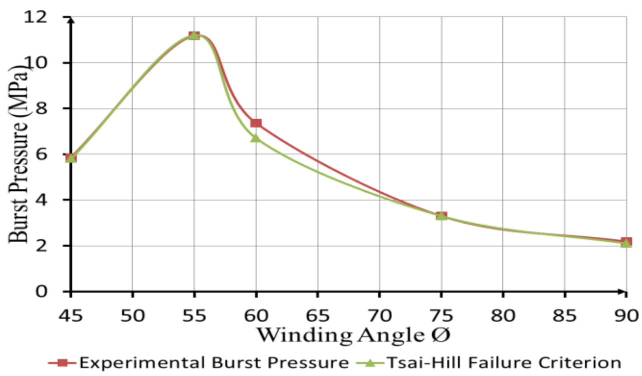


Fig. 11 - Comparative analysis between experimental results and Tsai-Hill failure criterion for $[\pm Ø°]_2$ E-glass fibers/epoxy orthotropic tubes

Results of the three criterions used are very close to the experimental outcomes. Whereas both Tsai-Hill and Hoffmann models seem to slightly underestimate the burst pressure (but still within the acceptable range of error), Tsai-Wu was found to be most fitting to the experimental results.

Maximum burst pressure occurs at 55° winding angle as theoretically predicted at a pressure of 10.9 MPa for using Tsai-Wu, 11.2 MPa for using Tsai-Hill and 10.6 MPa for using Hoffman theory, in contrast to an experimental value of 11.18 MPa. Fig, 13 shows the expected burst pressure for the range of winding angles from $[\pm 0°]_2$ to $[\pm 45°]_2$ which are not experimentally proven. The results confirm that the 55° winding angle provides the optimum setup. The $[\pm 0°]_2$ layup shows the lowest burst pressure record for all anti-symmetrical layups.

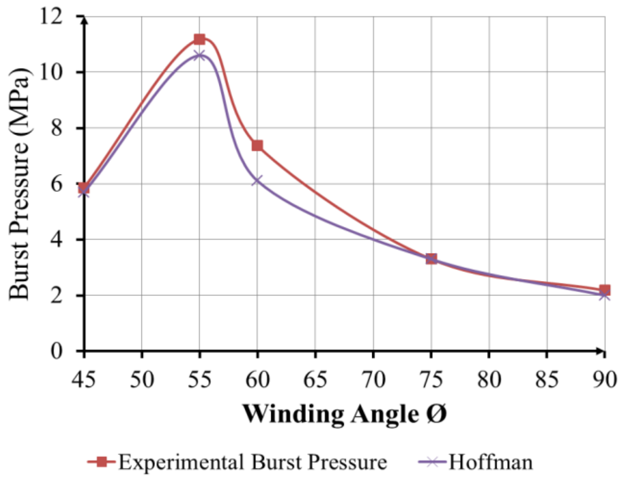


Fig. 12 - Comparative analysis between experimental results and Hoffman failure criterion for $[\pm Ø°]_2$ E-glass fibers/epoxy orthotropic tubes

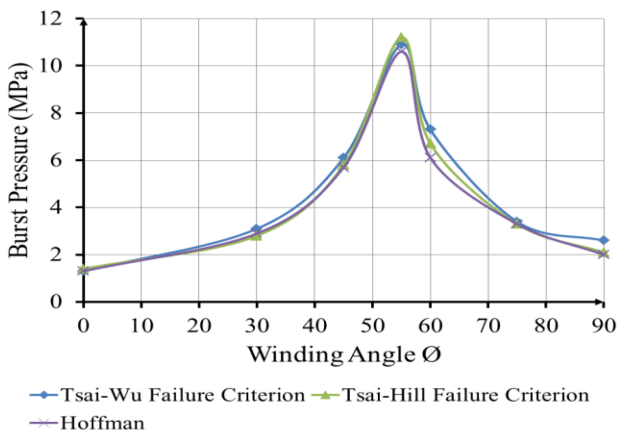


Fig. 13 - FEA results for variation of burst pressure with different winding angle for $[\pm Ø°]_2$ E-glass fiber/epoxy orthotropic tubes

B. Analysis of carbon fiber/epoxy and aramid/epoxy pipes

Proving good agreement with experimental data, the same FEA model is adopted for the analysis of different composites. Carbon fiber/epoxy and aramid/epoxy are selected for this analysis. Table 3 shows the respective properties used in the FEA [16-19]. The burst pressure is predicted for the following set of plies $[\pm 0°]_2$, $[\pm 30°]_2$, $[\pm 45°]_2$, $[\pm 55°]_2$, $[\pm 60°]_2$, $[\pm 75°]_2$, and $[\pm 90°]_2$.

Analysis results of the burst pressure for pipes made of carbon fiber/epoxy composites at different winding angles using the various failure criterions are shown in Fig. 14. Maximum burst pressure occurs at $[\pm 55°]_2$

with a pressure of 29.4 MPa for Tsai-Wu criterion, 28.8 MPa for Tsai-Hill and 27.1 MPa for Hoffman. The minimum burst pressure occurs at $[\pm 0°]_2$ with a value of 0.93 MPa for both Tsai-Hill and Hoffman criterion compared with 0.95 MPa for Tsai-Wu.

Table 3: Properties of carbon fiber/epoxy and aramid fiber/epoxy composites

Property		Carbon Fiber/Epoxy	Aramid /Epoxy
Young's Modulus	E_x (GPa)	127.7	83
	$E_y = E_z$ (GPa)	7.4	7
Poisson's Ratio	$V_{xy} = V_{xz}$	0.33	0.41
	V_{yz}	0.188	0.4
Shear Modulus	$G_{xy} = G_{xz}$ (GPa)	6.9	2.1
	G_{yz} (GPa)	4.3	1.86
Tensile Strength	X_t (MPa)	1717	1377
	$Y_t = Z_t$ (MPa)	30	18
Compression Strength	X_c (MPa)	-1200	-235
	$Y_c = Z_c$ (MPa)	-216	-53
Shear Strength	$S_{xy} = S_{yz} = S_{xz}$ (MPa)	33	34

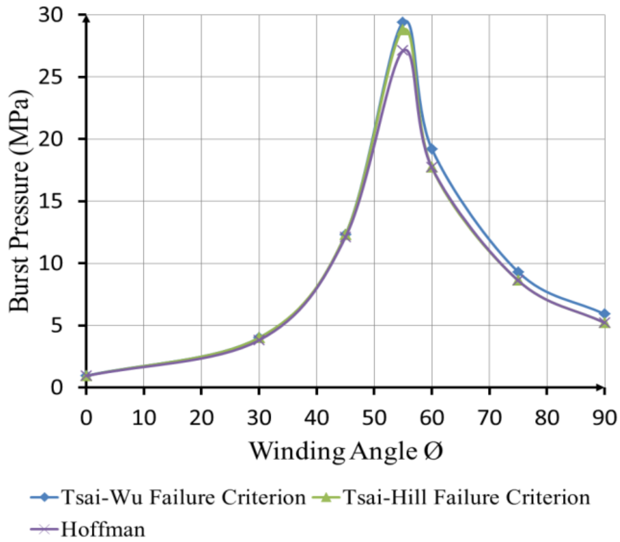


Fig. 14 - FEA results for variation of burst pressure with different winding angle for $[\pm Ø°]_2$ carbon fiber/epoxy orthotropic tubes

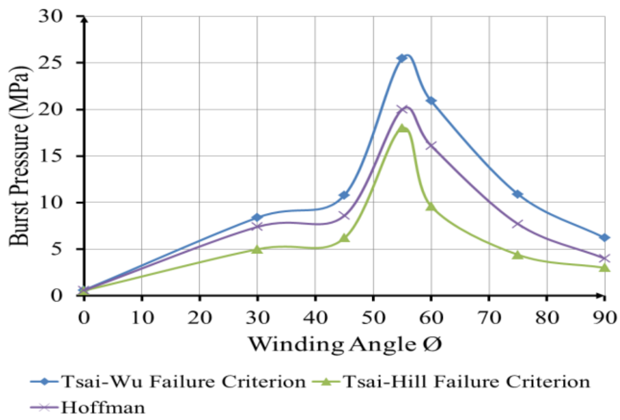


Fig. 15 - FEA results for variation of burst pressure with different winding angle for $[\pm Ø°]_2$ aramid fiber/epoxy orthotropic tubes

Fig. 15 shows the same analysis for aramid/epoxy, recording maximum burst pressure at $[\pm 55°]_2$ with a value of 25.5 MPa for Tsai-Wu criterion, 20 MPa for Hoffman criterion and 18 MPa for Tsai-Hill criterion. The minimum burst pressure was recorded to be about 0.6 MPa for the three criterions at $[\pm 0°]_2$. As a result the optimum winding angle is $[\pm 55°]_2$ verified for the three criterions. A Comparison of the analytical results using the Tsai-Wu criterion for E-glass/epoxy, carbon/epoxy and aramid/epoxy is shown in Fig. 16. FEA records show that carbon/epoxy pipes withstand maximum burst pressure through the variation of winding angle, followed by aramid/epoxy and finally E-glass/epoxy. Except for the range of winding angles from $[\pm 0°]_2$ to $[\pm 42°]_2$ aramid/epoxy shows higher resistance to pressure. Comparative analysis for the maximum induced Von-Mises stress just before failure for the three materials shown in Fig. 17.

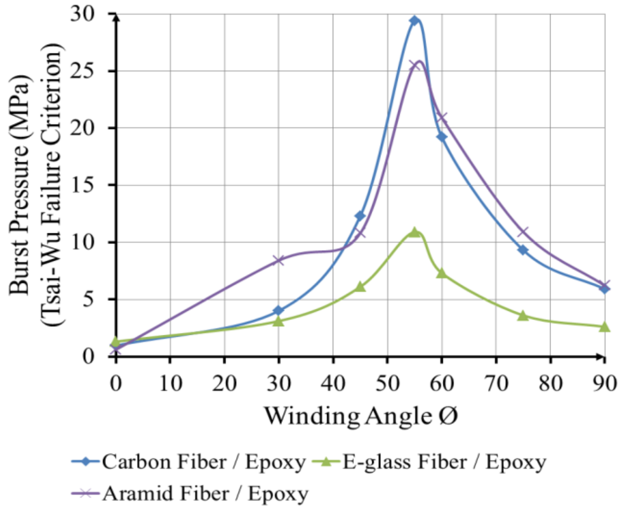


Fig. 16 - Comparing numerical burst pressure for different composite structures through different $[\pm Ø°]_2$

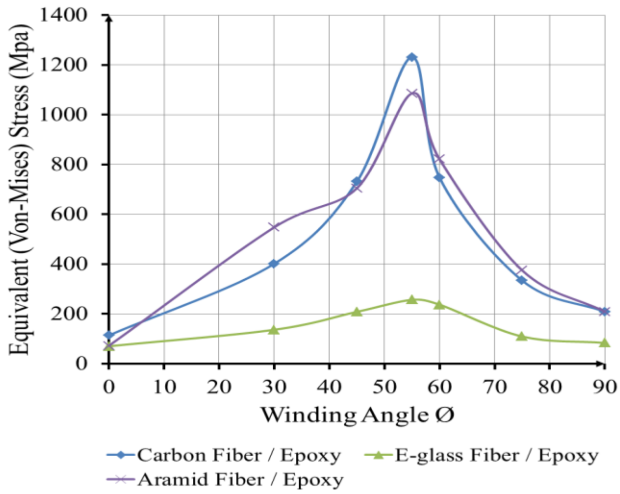


Fig. 17 - Comparing numerical equivalent stresses just before failure for different composite structures through different $[\pm Ø°]_2$

V. Discussion and Conclusions

This study was done to simulate the structural behavior of composite pipes subjected to internal pressure. Analysis for E-glass/epoxy applying LPF technique and Tsai-Wu, Tsai-

Hill and Hoffman failure criterions shows close prediction for the burst pressure compared to the experimental results.

FEA prediction of the burst pressure for a four layered filament wound composite pipes made of E-glass/epoxy, carbon/epoxy and aramid/epoxy composites using LPF concept concluded that the optimum winding angle is 55°. The lowest burst pressure was recorded to be at 0° winding angle. The burst pressure at the optimum winding angle $[\pm 55°]_2$ for the three materials E-glass/epoxy, aramid/epoxy and carbon/epoxy is predicted to be 10.9, 25.5 and 29.4 MPa respectively; where the burst Pressure for Carbon/epoxy is about three times that for E-glass/epoxy. The burst pressure for $[\pm 0°]_2$ comparing the three composites is almost the same. For $[\pm 90°]_2$, carbon/epoxy and aramid/epoxy results to about double the burst pressure for E-glass/epoxy.

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Ahmed W. Abdel-Ghany, B.Sc. is a teaching assistant at the “Design and Production Engineering” Department of Ain Shams University in Cairo – Egypt. His current research interests are in the areas of composite materials, stress analysis, and modeling and simulation of mechanical systems using FEA. Ahmed W. Abdel-Ghany has worked for three years in the Technical Research and Development Department, Egyptian Air Forces.

Iman Taha, Ph.D is an Associate Professor at the “Design and Production Engineering” Department of the Ain Shams University in Cairo – Egypt. The main research interests lie in the field of polymers and polymer composites, their development, processing and characterization technologies. Iman Taha has above 20 international publications, covering the above mentioned field, especially in combination with renewable resources.

Samy J. Ebeid, Ph.D is an Emeritus Professor at the “Design and Production Engineering” Department of Ain Shams University in Cairo – Egypt. The main research interests lie in the fields of Recent Manufacturing Processes (ECM – EDM – LASER – RP …etc), Machine Design and Stress Analysis. Samy J. Ebeid has above 50 local and international publications covering the mentioned fields. Samy J. Ebeid is also a referee for international journals in addition was a member of the Egyptian scientific committee for the promotion of professors and a member of the Egyptian national committee for welding technology.