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The influence of production inconsistencies on the functional failure of GRP pipes

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Abstract. In this study, a progressive damage modeling is developed to predict functional failure pressure of GRP pipes subjected to internal hydrostatic pressure. The modeling procedure predicts both first-ply failure pressure and functional failure pressure associated with the weepage phenomenon. The modeling procedure is validated using experimental observations. The random parameters attributed to the filament winding production process are identified. Consequently, stochastic simulation is conducted to investigate the influence of induced inconsistencies on the functional failure pressures of GRP pipes. The obtained results are compared to realize the degree to which random parameters affect the performance of the pipe in operation.

Keywords: composite pipes; functional failure; progressive modeling; stochastic analysis

1. Introduction

Thanks to high strength and stiffness, low weight and high corrosion resistant of composite materials, various industries have been encouraged to take advantage of them as a promising replacement for traditional materials. Among different industries, the civil infrastructure sector is the major consumer of composites (Hollaway 2010). Glass fiber Reinforced Polyester (GRP) pipes are broadly used for sewage, service and potable water transmission systems. Furthermore, due to the inherent smooth internal surface which remains the same during the service life, GRP pipes convey fluids with lower fluid loss than other concrete, steel or asbestos pipes (AWWA M45 2005). From installation point of view, easy joining system and also low installation costs have rendered GRP pipes as a good candidate for renovating old pipeline systems. Dictated by international standard (ANSI/AWWA C950 2001), the most important design constraint for GRP pipes is the soundness of the pipe against internal pressure. They need to maintain a certain level of hydrostatic pressure which is two times of their working pressure without any sign of weeping, leakage or fracture of the pipe wall as the short-term hydrostatic test.

Subjected to the internal pressure, GRP pipes most commonly experience leakage mode of failure classified as functional failure (FF). This mode of failure implies on a certain pressure that the fluid finds a path through the pipe wall thickness as a consequence of weepage phenomenon.

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The main reason that this failure is called as FF is placed behind this fact that the failed pipe cannot sustain its mission anymore due to the experienced leakage; while from structural point of view it would be able to support the loading. Thus the pipe is failed from functional viewpoint. Therefore, predicting the FF pressure of GRP pipes play an important role in their design procedure.

Different studies have been carried out on failure analysis of GRP pipes in literature. The majority of studies have conducted experimentally and limited theoretical investigations have been devoted to the prediction of the FF of GRP pipes. Rousseau *et al*. (1999) studied the damage behaviour of filament-wound pipes experimentally under various loading. Cohen (1997) studied relationship between fiber volume fraction in filament wound composite vessels and failure pressure. Melo *et al*. (2010) evaluated short term hydraulic failure pressures of a GRP pipe, experimentally and also predicted this value. Tarakcioglu *et al*. (2001) have studied the effect of surface cracks on the strength of glass/epoxy filament wound pipes both theoretically and experimentally. Ellyin *et al*. (1997) studied stress-strain and failure behavior of multidirectional filament wound fiberglass/epoxy tabulars under various stress ratios (axial stress/hoop stress) experimentally. Chang (2000) used acoustic emission technique to identify first ply failure of filament wound pressure vessels. The obtained results showed a good agreement with failure criteria such as Hoffman, Hill and Tsai-Wu. Meijer and Ellyin (2006) recorded failure envelopes for filament wound glass fiber reinforced epoxy tubulars. They performed multi-axial tests under various ratios of axial stress and circumferential stress in an MTS testing system on tubes produced by filament winding technique and reported the first observed mode of failure. A numerical and experimental study was carried out by Martins *et al*. (2013) to investigate the failure pressure of filament wound composite tubes for small tubes (about 100 mm as diameter) with closed-end loading conditions and subjected to internal pressure. They implemented an alternative damage model using the user subroutine (UMAT) in ABAQUS commercial software to perform the progressive damage modeling. Martins *et al*. (2013) also studied the effect of hoop/axial stress ratio on fracture morphology of filament wound composite pipes and performed a comparative study between two boundary conditions of closed-end and restrained ends both experimentally and numerically. Rafiee and his co-workers (Rafiee and Amini 2014, Rafee and Reshadi 2014) have developed a progressive damage modeling for predicting the FF pressures of both GRP pipes and GRP mortar pipes using deterministic approach. They have studied the influence of winding angles and fiber volume fractions on the FF pressure of GRP pipes. The influence of incorporating core materials into GRP pipe wall constructions on the FF of GRP mortar pipes have been studied in another research.

Performing a review on literature it can be understood that all theoretically conducted studies have been used deterministic approaches for the failure analysis of GRP pipes.

Recently, some remarkable efforts devoted to the study of random behavior of composite materials in literature. Onkar *et al*. (2007) predicted the statistics of First-Ply-Failure (FPF) of orthotropic plates with random material properties under random loading using stochastic finite element. They adopted Tsai-Wu and Hoffman criteria to predict the FPF load and first-order perturbation technique was used to derive the mean and variance of failure statistics. An application of spectral stochastic finite element method in a composite panel subject to random loads and constitutive properties was demonstrated by Ngah and Young (2007). Noh (2011a) used stochastic finite element method to analyze the displacement of composite plates considering randomness of material properties. He has presented a formulation of SFEM based on perturbation techniques to determine the response variability in laminate composite plates considering the randomness of material parameters and their correlations. Noh (2011b) also derived the SFEM formulation by accounting the spatial randomness of Poisson's ratio for laminated composite plates. Tee *et al*. (2013) have analyzed probabilistic failure of underground flexible pipes due to corrosion induced deflection, buckling, wall thrust and bending stress subjected to externally applied loading. They have numerically predicted probability of failure for a buried steep pipe using Hosofer-Lind and Rackwitz-Fiessler algorithm and Monte Carlo simulation.

The main objective of this study is to perform a stochastic modelling for predicting the FF pressures of GRP pipes. A Monte Carlo technique is used taking into account the inconsistencies arisen from GRP pipe production.

2. Experimental study

Fabricated using reciprocal filament winding method, 5 pieces of pipes with 700 millimeter diameter and 12 meter length were produced. In this process, the inner layer (also called liner) is firstly fabricated using stitched glass fiber mat (450 g/m^2), surface mat (30 g/m^2) and unsaturated polyester resin on a cylindrical mandrel. The approximate thickness of the liner is 1.5 millimeter. After curing liner using infrared heaters, reciprocal winding process is utilized to fabricate structural layers on the liner. A bundle of E-glass direct roving comprising of 42 strands with the bandwidth of 180 millimeters is impregnated in unsaturated polyester resin and then wound around the liner layer. In filament winding of GRP pipes, a filament bundle consisting of defined numbers of roving strands is used instead of single roving strand to reduce the production cycle time. The fabricated structural layers with configuration of $[90/\pm 60_3]$ are also cured for a certain time while the pipe is kept rotating on the mould. It should be noted that mentioned angles in the ply configuration are measured from longitudinal axis of the pipe.

The mechanical properties of the glass fiber and resin are given in Table 1. Known as TEX, the weight of roving in grams per kilometer (1000 meters) is 2400. The average fiber volume fraction of the pipes is obtained as 57.14% following the mentioned procedure in ASTM D 3171 (2006).

Each pipe is kept for a week to accomplish the post-cure process and then it is placed in a hydrostatic pressure testing apparatus in Fig. 1. The ends are sealed using blind FRP flanges and double o-rings. Both ends are free to slide on the o-rings, so no axial loading is induced in the pipe. The axial force of blind flanges is reacted out by the tie bars mentioned in the test apparatus. Expelling all entrapped air inside the pipe, the pipe is filled with water. Internal pressure is applied and increased gradually till the weepage is observed. Formation of droplets on the exterior surface of the pipe is the sign of FF.

Table 1 Mechanical properties of direct roving and orthotropic polyester resin

Mechanical properties	Fiber	Matrix
Young modulus (GPa)	70	3.5
Shear modulus (GPa)	28.69	1.32
Poisson's ratio	0.22	0.33
Tensile strength (MPa)	1970	78
Compressive strength (MPa)	-	130
Density (g/cm^3)	1.15	2.56

Fig. 1 Hydrostatic pressure testing machine (By courtesy of ALH Co., Iran)

According to the experimental reports, the FF pressures are measured as $2.7^{+0.12}_{-0.18}$ MPa. Inspecting the pipe surface after the experiment, no evidence of structural failure in the failed region has been observed.

3. Modeling procedure

Progressive damage modeling is used to obtain FF pressures of the GRP pipes examined in experimental study. The modeling procedure consists of four steps of model preparation, stress analysis, failure evaluation and degradation of material properties. A brief explanation of the modeling steps is outlined as below.

3.1 Model prepration

A finite element (FE) model of the pipe is constructed using commercial FE package. SHELL99 element is selected from the element library. The thickness of each ply is calculated using below formulations

$$t_{cross} = \frac{2 \times \rho_A^C}{\rho_{FRP} \times W_f} \tag{1}$$

$$t_{hoop} = \frac{\rho_A^H}{\rho_{FRP} \times W_f} \tag{2}$$

where t_{cross} and t_{hoop} is the thickness of cross layers in the form of [±Θ] and the thickness of hoop layers wherein fiber are along circumferential direction, respectively. Other parameters reflected in above formulations are determined using the following equations

$$W_f = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m} \tag{3}$$

$$\rho_{FRP} = \left(V_f \rho_f + V_m \rho_m\right) \tag{4}$$

$$\rho_A^C = \frac{N_S T}{BSin\theta} \tag{5}$$

$$\rho_A^H = N_S T / B \tag{6}$$

where t_{cross} and t_{hoop} is the thickness of cross layers in the form of [±Θ] and the thickness of hoop layers wherein fiber are along circumferential direction, respectively. Other parameters reflected in above formulations are determined using the following equations.

3.2 Stress analysis

The in-plane stress components induced in each and every layer are obtained after performing a static analysis. Due to the small deformation experienced by the pipe, the linear static analysis is suitable for the purpose of this study. The results have been read in the mid-span of the pipe length avoiding end effect disturbance on the results. A macro is written in APDL of ANSYS to perform the whole procedure of FE modeling and analysis of any arbitrary composites pipes. The required input data by user is limited to the pipe diameter, type of boundary conditions, amount of internal hydrostatic pressure, lay-up configurations and mechanical properties of constituents, i.e., glass fiber and resin. The in-plane longitudinal, transverse and shear stress components of each and every ply are reported as the output of the code.

3.3 Failure evaluation

Obtaining on-axis stress components in each ply, the failure occurrence is evaluated using Hashin failure criteria. Hashin failure criteria not only considers the interaction of different stress components for the failure evaluation but also report the mode of failure. A simple method in the form of below equations is used to estimate strength components required for failure analysis.

$$X_T = X_f \left(V_f + V_m \frac{E_m}{E_f} \right) \tag{7}$$

$$X_C = 0.5 X_T \tag{8}$$

$$Y_T = V_m X_m \tag{9}$$

$$Y_C = V_m X'_m \tag{10}$$

where X_T, X_C, Y_T and Y_C are representative of longitudinal tensile strength, longitudinal compressive strength, transverse tensile strength and transverse compressive strength. X_f, X_m and X'_m stands for fiber tensile strength, matrix tensile strength and matrix compressive strength, respectively. The in-plane shear strength is also selected as 65 MPa for all cases as an average of shear strength for unidirectional FRP layers with different fiber volume fractions on the basis of experimental observations. Since the laminates will experience negligible shear stress in comparison with arisen stress components in longitudinal and transverse direction, this can be considered as a rational assumption.

It is observed that all layers experiencing either matrix cracking or shearing modes of failure which is attributed to the applied (1:0) load ratio. This was also confirmed by the FF of the pipes occurring by weepage phenomenon during the experimental observations.

3.4 Degradation rules

After occurrence of the failure in any layer, its mechanical properties are reduced using developed sudden degradation rules by Shokrieh and Lessard (2000) on the basis of experiencing mode of failure

$$(E_X, E_Y, \nu, G_{XY}, X_T, X_C, Y_T, Y_C, S)_{\text{int}\,act} \longrightarrow (E_X, 0.1E_Y, 0.1\nu, 0.1G_{XY}, X_T, X_C, 0, Y_C, S)_{failed} \quad (11)$$

$$(E_X, E_Y, \nu, G_{XY}, X_T, X_C, Y_T, Y_C, S)_{\text{int}\,act} \longrightarrow (E_X, 0.1E_Y, 0.1\nu, 0.1G_{XY}, X_T, X_C, Y_T, 0, S)_{failed} \quad (12)$$

$$(E_X, E_Y, \nu, G_{XY}, X_T, X_C, Y_T, Y_C, S)_{\text{int}\,act} \longrightarrow (E_X, 0.1E_Y, 0.1\nu, 0.1G_{XY}, X_T, X_C, Y_T, Y_C, 0)_{failed} \quad (13)$$

Eqs. (11) and (12) are associated with matrix tension and matrix compression and Eq. (13) deals with fiber/matrix shearing mode of failure.

3.5 Progressive modelling

A progressive modeling is employed to obtain FF of GRP pipes. The investigated pipe is subjected to the internal hydrostatic pressure and stress components in all layers are obtained using FEA. The occurrence of failure is examined in all layers. If failure happens, the mechanical properties of the corresponding layer are reduced; otherwise the internal pressure increases incrementally and the whole procedure is repeated. The procedure continues till all layers failed implying on the FF of comprising layers. The whole mentioned procedure is executed using a written computer code in MatLab. The computer code employs ANSYS for the stress analysis stage.

3.6 Model validation

Developed modeling procedure is executed to obtain the internal pressure associated with the FF of investigated GRP pipe in experimental study. For deterministic analysis, the obtained fiber volume fraction for produced pipes, i.e., 57.14%, is selected. It is observed that the first ply failure (FPF) occurs at the pressure of 1.16 MPa in the first laminate experiencing matrix cracking mode of failure. The modeling continues till all plies are failed due to matrix cracking which is representative of a weepage throughout the whole plies. The obtained FF pressure is 2.58 MPa which is in a very good agreement with experimentally measured mean pressure of 2.7 MPa. The main reason that the theoretically predicted FF pressure is lower than that of experimentally measured value is originated from neglecting liner layer in the modeling procedure.

4. Stochastic analysis

The main parameters affecting the mechanical behavior of GRP pipes are fiber volume fraction and winding angles in cross plies. As a consequence, these two parameters play a key role in defining the FF pressures of GRP pipes. From practical point of view, fiber volume fraction and winding angle cannot be adjusted very accurately during the production process of GRP pipes. It was previously observed by Rafiee and Amini (2014) that the FF pressures of a GRP pipe is strongly sensitive to these two parameters. The strong dependency of the mechanical behavior of GRP pipes to the fiber volume fraction can be traced in Eqs. (1) to (4). In other words, fiber volume fraction will influence both thickness and mechanical properties of each ply. Moreover, the winding angle is the main parameter affecting on-axis stress distributions. Subsequently, treating both fiber volume fraction and winding angle as random parameters, stochastic analysis instead of previously deterministic simulation is conducted. Fiber volume fraction varies between 50% and 60%. The mentioned interval is obtained practically by analyzing fiber volume fractions of different samples taken from different produced pipes employing current discontinuous filament winding machinery. The winding angles are most often deviated about 1.5 degree from the nominal winding angle in cross plies in the filament winding process of GRP pipes. Namely, for the investigated pipe in this article, the winding angle is randomly selected between 58.5° to 61.5° for cross plies; while the angle of hoop ply is fixed. Normal distribution with the mean value of 60° is chosen as a probability density function for winding angle in cross plies.

It is noteworthy that in the stochastic analysis, the fiber volume fraction of each and every ply is selected randomly in order to simulate more realistic situation of filament winding process.

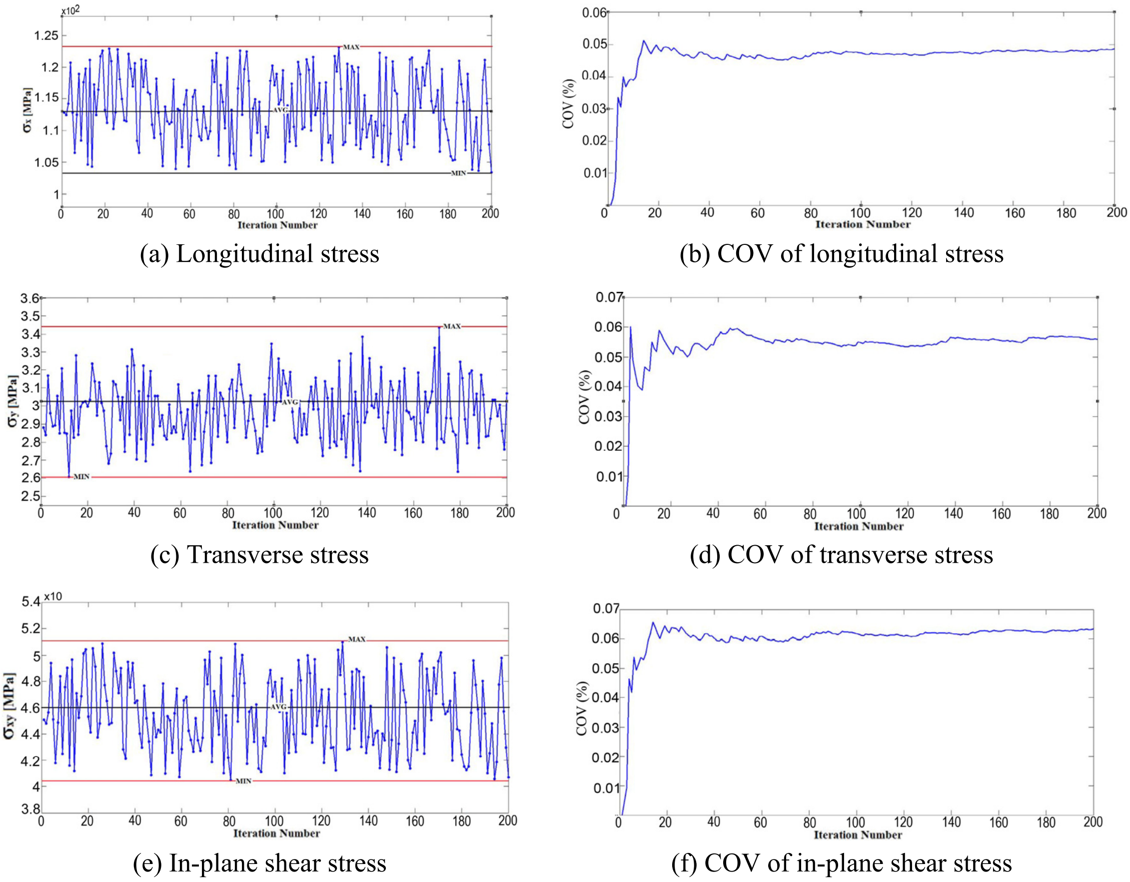
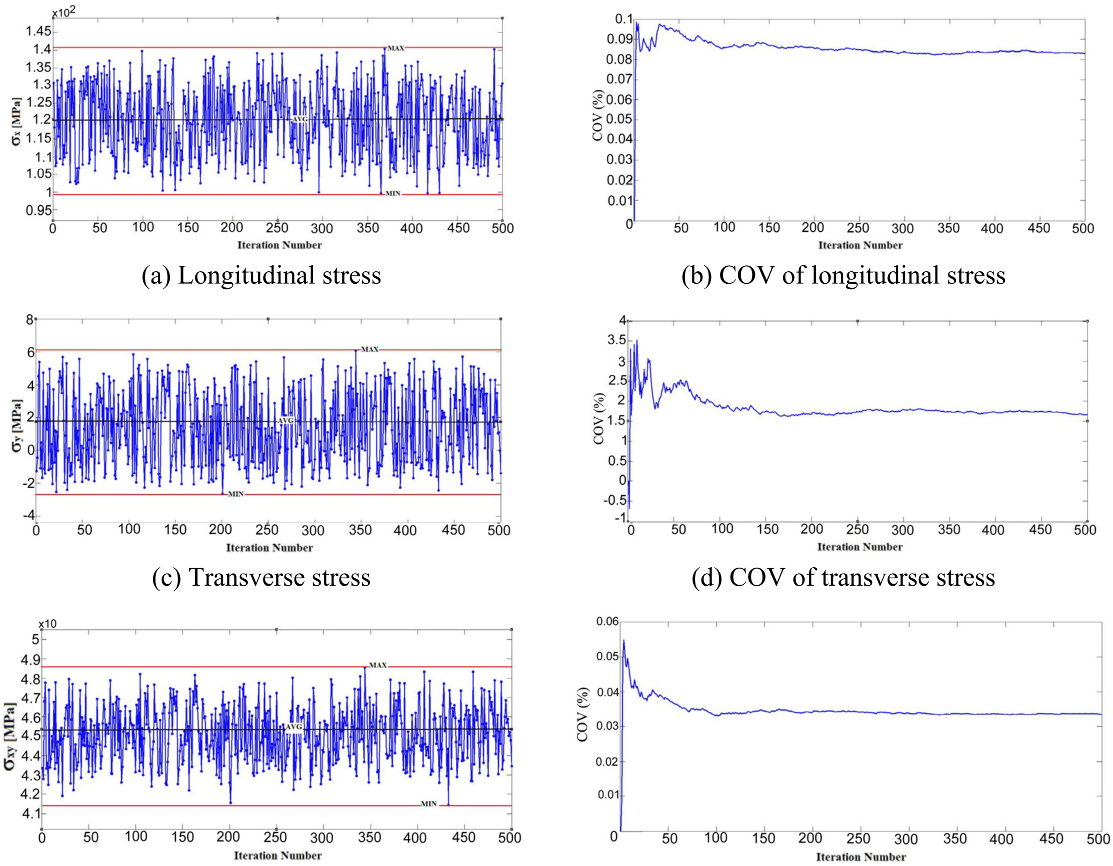


Fig. 2 Stress components for random fiber volume fraction



(a) Longitudinal stress (b) COV of longitudinal stress

(c) Transverse stress (d) COV of transverse stress

(e) In-plane shear stress (f) COV of in-plane shear stress

Fig. 3 Stress components for random winding angle of cross plies ($V_f = 57.14\%$)

Namely, different fiber volume fraction is randomly assigned to each ply following a normal distribution with average of 55%.

Since the most important part of the modeling for obtaining FF pressures is the stress analysis, stochastic stress analysis is conducted to study the degree to which on-axis stress distributions are changed. For this purpose, Monte Carlo method (Kleiber and Hien 1992) is used and the stress analysis section of the whole modeling procedure is executed. At the first stage, just fiber volume fraction is considered as a random variable, while the winding angles of cross plies are fixed at ±60°. The obtained results for all longitudinal and transverse stress components, i.e., longitudinal, transverse and shear stress components are presented in Fig. 2 accompanied with corresponding coefficient of variation (COV) versus number of realizations. The internal pressure is 1 MPa for the results presented in Fig. 2.

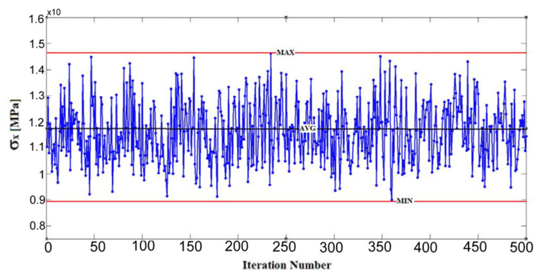
It can be understood from presented results in Fig. 2, that producing 200 samples is sufficient for obtaining plateau region in COV graphs implying on the convergence of results.

At the second stage, the fiber volume fraction is selected constantly as 57.14%, while the winding angle in the cross plies are randomly selected complying with the pattern of $60° \pm 1.5°$. The in-plane stress distribution and corresponding COVs are presented in Fig. 3. The internal pressure is 1 MPa for the presented results in Fig. 3. It could be understood that plateau region in COV graphs is met when 500 numbers of realizations are produced by the stochastic analysis.

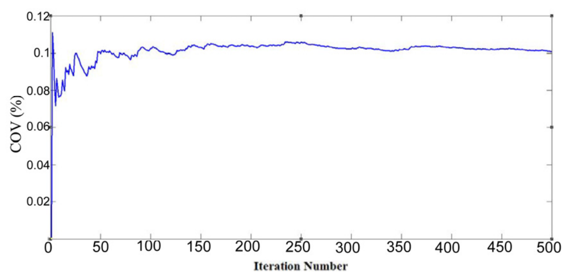
Finally, both random fiber volume fractions and winding angles of the cross plies are selected randomly. The obtained results for in-plane stress components are presented in Fig. 4. It should be noted that 500 numbers of realizations are generated to obtain plateau region in COV graphs as a showing convergency in results.

The stochastic analysis of the FF pressures is conducted considering obtained results for the stress components. The whole integrated procedure of predicting FF pressures is executed stochastically. Based on the convergence study of stochastic stress analysis, the written code is implemented 500 times. The obtained results are presented in Table 2.

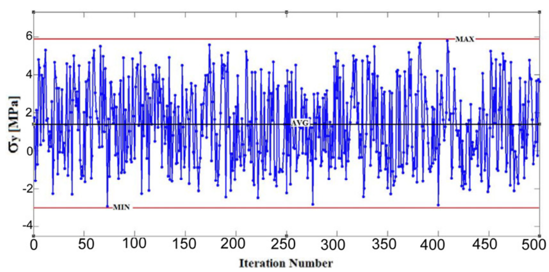
As it can be seen from presented results, FPF happens in 90-degree ply. The higher fiber volume fraction in 90-degree ply will reduce the FPF pressure. This happens due to the reduction in transverse strength in accordance with Eqs. (9) and (10). Moreover, when the fiber volume fraction increases, the thickness of plies reduced considerably according to the Eqs. (1) to (3). Thus, the induced off-axis stress in the ply increases.



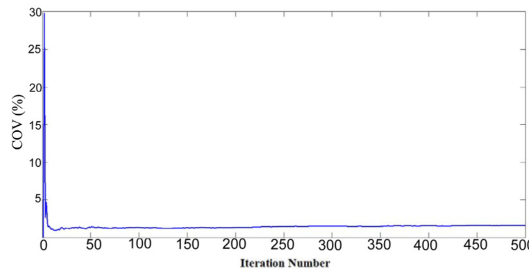
(a) Longitudinal stress



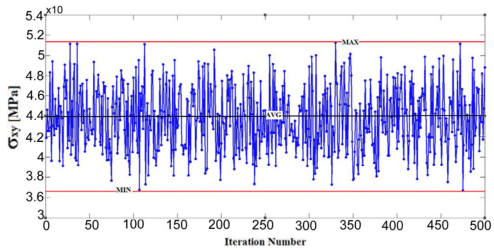
(b) COV of longitudinal stress



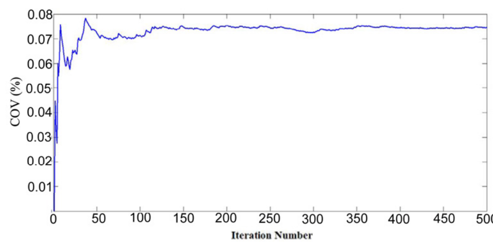
(c) Transverse stress



(d) COV of transverse stress



(e) In-plane shear stress



(f) COV of in-plane shear stress

Fig. 4 Stress components for random winding angle and random fiber volume fraction

Table 2 Results of stochastic FF pressures for the [90/±60_3] GRP pipe

	FPF pressure (MPa)			FF pressure (MPa)		
	Stochastic analysis		Deterministic analysis	Stochastic analysis		Deterministic analysis
	Min	Max		Min	Max	
Failure pressure	0.98	1.46	1.16	2.39	2.64	2.58
Fiber volume fraction	59.20%	50.80%	57.14%	50.00%	50.01%	57.14%
Winding angle	90°	90°	90°	55.85°	61.5°	60°

On the other hand, the presented results for FF pressure shows that FF varies between 2.39 and 2.64 MPa taking into account manufacturing inconsistencies, while deterministic analysis approaches to the certain value of 2.58 MPa. It is also observed that increasing the angle of winding in cross plies (measured from longitudinal axis of the pipe) has a positive consequence on the FF pressure of the pipe. Comparing the maximum value of FF pressures with the results obtained through deterministic analysis, it can be understood that the negative influence of higher portion of fiber volume fraction can be compensated by adjusting the winding angle. It should be emphasized that in stochastic analysis, the fiber volume fraction of each ply is selected randomly and reported values in Table 2 imply on the fiber volume fraction of the corresponding ply experiencing failure and it is not the average of fiber volume fraction for the whole structure.

5. Conclusions

A progressive damage modeling is developed to predict functional failure of GRP pipes subjected to internal hydrostatic pressure. The modeling consists of four main sections as model preparation, stress analysis, failure evaluation and material degradation. The pipe is subjected to an initial internal pressure as the starting point of simulation and stress distributions in all comprising layers are extracted using FEM. The occurrence of failure in each and every layer is evaluated carefully. If failure is not identified, the internal pressure increases for the next step of solution. In case of failure in any layer, the corresponding mechanical properties are degraded in accordance with the experienced mode of failure and the whole procedure repeats. The modeling continues till the weepage failure is reported representing functional failure of GRP pipes. The accuracy of the developed modeling procedure is examined using experimental observations on the GRP pipes subjected to the hydrostatic tests as the case study.

Then, the influence of production inconsistencies on the functional failure of GRP pipes is investigated. For this purpose, developed modeling procedure is implemented stochastically taking into account both fiber volume fraction and winding angles as the main random variables. Firstly, a convergence study is conducted to extract sufficient number of realizations on the basis of in-plane stress distributions. Then, stochastic determination of the functional failure is conducted to study the degree to which random behaviors of production parameters affect the mechanical performance of produced GRP pipes.

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