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Original scientific paper

The Design of Glass Fiber//Epoxy Composite Pipes by the Implementation of the Full Factorial Experimental Design

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Abstract: In the present work, the attempt was made to assess the applicability of the full factorial experimental design in predicting the hoop tensile strength of glass fiber/ epoxy resin composite pipes by using of a split disk specimens. Split disk tension tests, provide reasonably accurate information with regard to the apparent tensile strength of composite pipe.

In the study we used a number of composite pipes with different fiber orientation, fiber tension and velocity of the winding. The composite pipes were made by using of filament winding technology includes winding of resin impregnated fibers into a tool and hardening of the wound structure.

The preparation of the composite experimental samples was conducted in accordance with the 2^3 full factorial experimental design. The winding speed of the composites was taken to be the first factor, the second was the fiber tension and the third winding angle. The first factor low and high levels were set at 5,21 m/min and 21 m/min, respectively, for the second factor – at 64N and 110N, respectively, and for the third factor – at 10^0 and 90^0. To approximate the response i.e. the hoop tensile strength of the composite pipes within the study domain (5,25 – 21) m/min x (64-110)N x $(10 – 90)^0$, the first order linear model with the interaction was used. The influence of each individual factor to the response function was established, as well as the influence of the interaction of the two and three factors. We found out that the estimated first-degree regression equation with the interaction gave a very good approximation of the experimental results of the hoop tensile strength of composites within the study domain.

Keywords: factorial design, regression equation glass fibers, composite pipes, filament winding.

Introduction

Properties of composites arise as a function of its constituent materials, their distribution, and the interaction among them and as a result of it an unusual combination of material properties can be obtained. Basically, the properties of fiber reinforced composites depend on the properties of its components, their volume ratio, the orientation of the fibres in the matrix and the properties of the fibre-matrix bond. The mechanical properties of fibre-polymer bonds are mainly determined by the adhesion and the mechanical compatibility between the fibres and the matrix as well as the angle between the fibres and the direction of loading. In order to obtain a good mechanical interaction between the fibres and the matrix, their mechanical parameters must be adapted to each other. The approximate linear-elastic deformational behaviour of the composite is governed primarily by the reinforcing fibres. In order to prevent the development of microcracks in the matrix before reaching the fibre's elongation limit, the failure strain of the matrix should be greater than that of the fibres. Under compression, however, a minimum stiffness of the matrix is required to prevent buckling of the fibres. Stiffness and strength of a fibre-matrix bond depend greatly on the angle between the fibres and the direction of loading [1-4].

For choosing the technology of manufacturing of the fiber reinforced composite element one should consider anticipated number of elements to produce, their shape and their dimensions. Of great importance are also requirements referring to tensile strength, Young´s modulus and other properties such as accuracy of dimensions, quality of the surface, etc. There are various methods of manufacturing, from manual to fully-automated, but filament winding is a very important and widely used technique for fiber reinforced composites production [5].

The basis of this technology includes winding of resin-impregnated fibers into a tool and hardening of the wound structure. This technology enables the fiber to be placed into the direction of the load that may be expected during their exploitation. Owing to this unique capability, the mechanical properties of fibers in the longitudinal direction can be maximally exploited. Based on that, it is clear that the filament winding technology is used for creating new materials with distinct anisotropy according to the direction in which the fiber is placed. In other words, different directions result in a material with different mechanical properties. Thus produced composite materials have the highest percent of fibers of all composite materials and small density. This fact is important for loaded elements of construction, which also need to have small mass. By varying the winding angle with respect to the mandrel axis, directional strength can be obtained by considering the loads, which will operate on the finished product. It is essential to know the mechanical characteristics of filament wound tubes in order to employ them in design applications [6-9].

Fiber reinforced polymer composites are considered as a substitute for components or systems that are constructed of traditional materials, namely metal, due to their properties such as: lightweight, corrosive resistant, high specific strength and specific stiffness, ease of construction and given possibility of their design to satisfy performance requirements. Due to the limited understanding of the behavior of these structures under internal pressure their usage has been limited. Therefore, glass fiber reinforced pipes are designed either for gravitational or pressurized transportation of fluids and usually they are tested under ring deflection or internal pressure conditions [10,11].

The purpose of this study, was to assess the applicability of the full factorial experimental design in predicting the hoop tensile strength of glass fiber/ epoxy resin composite pipes.

Material and Methods

The thermosetting epoxy resin Araldite LY564/Aradur 917/Accelerator 960-1 from Huntsman was used as a matrix. As reinforcement, a glass fiber roving 185P with 1200tex from Owens Corning was used. The impregnation of the fibers and their winding was carried out on a laboratory filament winding machine MAW FB 6/1 with six axes, roller type, and resin bath manufactured from Mikrosam A.D. The basis of this technology includes winding of resin-impregnated fibers into a tool (mandrel) and hardening of the wound structure. Glass fibers pass through a resin bath and gets wet before winding operation. After the winding of the fibers the composite pipes were fully curing i.e. cross-linking of the resin with industrial heater at temperature of 80^0C and 140^0 within 240 minutes on the both temperatures. After the curing operation, the removal of the mandrel from the specimens was performed. Glass/epoxy composite pipes were taken in this study because of the cost favorability compared to high-performance fiber composite pipes.

During the impregnation of the fibers, several factors were observed (resin viscosity, speed of impregnation, temperature) so that the required resin content in the composite pipes was attained (mass ratio fiber resin was 75:25 wt. %.).

In the 2^3 full factorial experimental design (FFED) we used in this study, the winding speed of the glass fibers is taken to be the first factor, the second factor is - fiber tension, and the third factor is – winding angle. For the first factor the low and high levels are set at 5, 25 m/min and 21 m/min, respectively, for the second factor – at 64N and 110N, respectively, and for the third factor – at 10^0 and 90^0. Within this relatively narrow region of winding angle of the fibers, the linear dependence of the hoop tensile strength vs. winding angle was assumed. With that assumption, we took the first order linear model with interactions to predict the response function i.e. the hoop tensile strength of the composites within the stated study domain (5,25 – 21) m/min x (64 - 110)N x $(10\text{-}90)^0$.

The full factorial experimental design allows making mathematical modeling of the investigated process in the vicinity of a chosen experimental point within the study domain [3,4]. To include the whole study domain we chose the central points of both ranges to be the experimental points. For the winding speed of the composites, we chose the experimental point to be 13,125 m/min, for the fiber tension – 87N and for the winding angle, the experimental point – 50^0 (which corresponds to previously defined levels).

All tests were conducted with a biaxial/combined loading of split-disk test specimens according to ASTM D2290 [2]. Proposed ring shape of samples may be applied in axial tension test, internal pressure test, etc., as well as their combinations. Split-disk tests are very efficient in determine the performance of tubular structures which are usually used under internal pressure developing high hoop [2, 7, 8].

Figure 1 shows split disk test specimen and test fixture. The hoop tensile strengths are calculated in accordance with the ASTM D2290.

In accordance with the FFED procedure, 8 (2^3) trials are needed i.e. all possible combinations of the variables are tested.

The coding of the variables is conducted in accordance with Table 2.

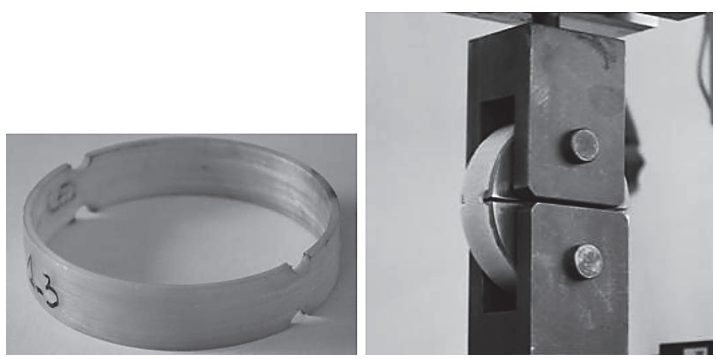

Fig. 1. Split disk test specimen and test fixture

Table 1. Coding convention of variables

	Winding speed, m/min	Fiber tension, N	Winding angle, ^{0}
Zero level, $x_i = 0$	13,125	87	50
Interval of variation	7,875	23	40
High level, $x_i = +1$	21	110	90
Lower level, $x_i = -1$	5,25	64	10
Code	x_1	x_2	x_3

Results and Discussion

The test results are presented in Table 2 together with the experimental matrix.

Table 2. Experimental matrix with results

Trials	x_1	x_2	x_3	$x_1\ x_2$	$x_1\ x_3$	$x_2\ x_3$	$x_1\ x_2\ x_3$	Composite pipes $\sigma_{average}$, MPa
1	-1	-1	-1	+1	+1	+1	-1	830,275
2	+1	-1	-1	-1	-1	+1	+1	780,465
3	-1	+1	-1	-1	+1	-1	+1	875,14
4	+1	+1	-1	+1	-1	-1	-1	725,845
5	-1	-1	+1	+1	-1	-1	+1	25,32
6	+1	-1	+1	-1	+1	-1	-1	22,275
7	-1	+1	+1	-1	-1	+1	-1	17,0
8	+1	+1	+1	+1	+1	+1	+1	16,95
-1 Level	5,25	64	10					
+1 Level	21	110	90					

By implementing the 2^3 full factorial experimental design we found out that the response function in coded variables, y_k, is:

$$y_k = 411{,}66 + 25{,}27x_1 + 2{,}92x_2 + 391{,}27x_3 - 12{,}06\ x_1x_2 + 24{,}50\ x_1x_3 - 0{,}49\ x_2x_3 - 12{,}81x_1x_2x_3 \quad (1)$$

In the FFED the terms x_1x_2, x_1x_3, x_2x_3 and $x_1x_2x_3$ are the interaction between the factors which might also have the influence on the response, in our case hoop tensile strength (σ value).

By analyzing the regression equation it should be noted that the main positive contribution to the σ is given by the winding angle i.e. hoop tensile strength is directly proportional to the winding angle of the fibers in the composite pipes. The influence of the winding angle of the fibers is ten orders of magnitude greater than the influence of the winding velocity but the influence of the fiber tension is the lowest. The interaction of the two factors, has a negligible effect on the hoop tensile strength which is smaller than the influence of the factors separately. The interaction of the three factors, with the coefficient of – 12, 81 also has a negligible negative effect on the hoop tensile strength.

From the regression equation it can be noted that only the winding angle as a process parameter x_3 influence significantly on hoop tensile strength. The influence of the other two factors: winding speed and tension of the fiber affect insignificant on the tensile strength, and also there is no interaction between factors. So, they can be omitted in the regression equation:

$$y_k = 411{,}66 + 391{,}27x_3 \quad (2)$$

The response function in engineering or natural variables, y_n, is:

$$y_n = 9{,}78185 \cdot X_3 - 77{,}4326 \quad (3)$$

To validate the implementation of the FFED in the study and the assumed model, theoretically calculated results (Eq. 3) were compared with the experimental values for the composites with the winding angle of 10^0, 45^0 and 90^0 and the fixed winding speed of 21 m/min and winding velocity of 110N. This comparison can be conducted with any other value for the winding angle as long as it is within the study domain. The results are presented in Figure 2.

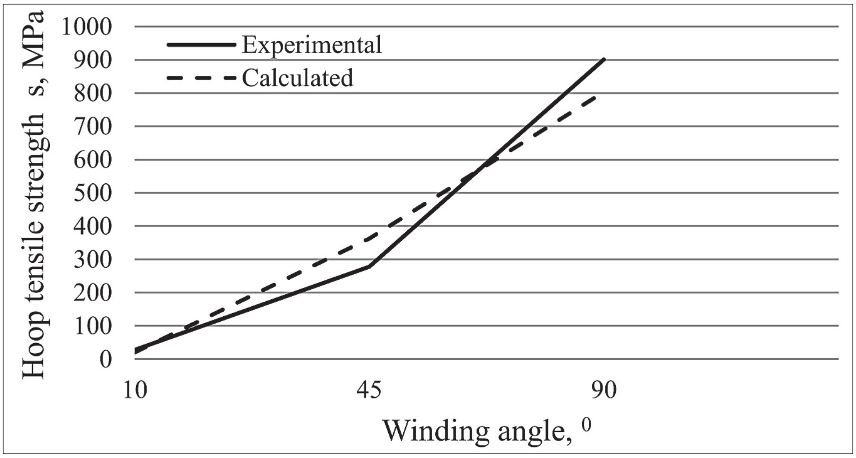

Figure 2. Theoretical vs. experimental values of tensile strength

As it can be seen in Fig. 2, there is a good agreement between calculated and experimental values of tensile strength. All calculated values are placed in a straight line which is in accordance with the assumed model of the experiment and are in close proximity of the experimental data.

Conclusions

For the range of the winding speed, winding velocity and winding angle the experimental measurements of the tensile strength of composite laminates were carried out by implementing the 2^3 full factorial experimental design. A correlation equation was established for tensile strength as a function of the winding speed, winding velocity and winding angle of the fibers and of the interaction between them. A very good agreement was found between experimental and calculated values. It was observed that if the study domain is precisely established (narrow enough), the full factorial experimental design can be employed in order to give good approximation of the response i.e. tensile strength value.

Tensile strength is directly proportional to the winding angel of the fibers in the composite pipes. The other two factors are not dominant factors than the winding angle.

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