Process Parameter Optimization of Single Lap-Bolt Joint Date Palm Fiber Reinforced Polyester Composite Using ANN-Genetic Algorism

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Abstract. Natural fiber reinforced polymer composites are widely employed in automotive, aerospace, and civil applications due to their high strength-to-weight ratios and these applications require joining composite. Bolt joining of composite materials is the most prevalent way of joining, due to its efficiency of transferring load and ease of disassembly. However, bolt joining of composite is largely influenced by geometrical parameters such as edge to diameter ratio (E/D), width to diameter ratio (W/D), and fiber orientation. This work emphases on the process parameters optimization of single lap bolt joint date palm fiber reinforced polyester composite (DPFRPC) to improve the joint strength. The study was conducted experimentally by making single lap bolt joining of DPFRPC under tensile testing. The important factors affecting the performance of the adhesively joint such as E/D (1.5, 2.5, and 3.5), W/D (2.5, 3.5, and 4.5), and fiber orientation (0/0°, 45/−45°, and 0/90°) was studied using L_9 orthogonal array experimental design. Artificial neural network (ANN) was used to model the experimental results. Genetic algorithm (GA) optimization technique was used to determine the optimum process parameters. Using this technique, the optimum parameters of single lap bolt joint DPFRPC were, 3.5 E/D, 4.5 W/D, and 56.5° fiber orientation, with a load carrying capacity of 9.52 kN.

Keywords: DPFRPC · Single lap · Bolt joining · ANN · GA · Tensile strength

1 Introduction

In today’s world, there are many more composite materials available. Researchers are more interested in natural fiber reinforced polymer matrix composite material because of its high strength-to-weight ratio [1, 2]. Amongst natural fibers, date palm fiber (DPF) specifically Phoenix dactyliferal, is the most cost-effective fiber with good physical and mechanical characteristics. The fiber can be extracted from all parts of date palm tree [3]. It is founded abundantly in Bahir Dar, Ethiopia. When date palm fiber and polyester are combined, gives date palm fiber reinforced composite (DPFRPC) with properties that are distinct from the ingredients [4, 5].

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In a variety of application domains, natural fiber reinforced composites (NFRPCs) are used in joined form for assembling purposes, since the making of long and complex geometry structure composite using a single mold is impractical and expensive [6]. NFRPCs cannot be welded due to their electrical nonconductivity. Adhesive joining, mechanical fastening, and hybrid joining can all be used to tackle this problem [7]. The type of composite joining is determined by the application area, the load to be transferred, and the weight of the joint [7, 8].

Bolt joining is the most prevalent way of joining several materials such as metal, nonmetals, and composites to each other and other materials [9, 10]. Furthermore, unlike adhesive joining, bolted joints have no environmental impact and transfer higher stresses between the joined structures. Several previous works evidenced that net tension, shear out, and cleavage failures exist under this joining method. Bolt joining can achieve 40–80% joint efficiency during joining of NFRPCs. Bolt joining of NFRPCs can be designed over the adhesive joint, if weight is not an issue [11]. In adhesive joining, there is no delamination due to the absence of holes and weight decrease. But it can’t be used for structures that require disassembly [12, 13].

The most prevalent and appropriate bolt joining methods are single and double lap joints. Single lap is preferred over double lap because of its simple geometry and high structural efficiency [6]. This research focuses on a single lap bolt joint of DPFRPC as indicated in Fig. 1 for a uniform cross-section in the NFRPC application area.

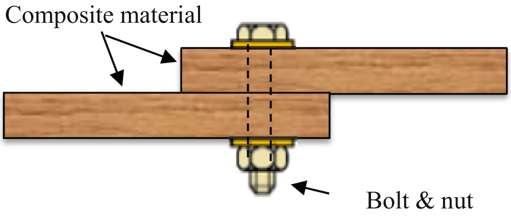


Fig. 1. Single lap bolt joining of composite material.

Drilling a hole is required, and damage happens at the beginning and end of the drilling operation [14]. The fiber layers peel up as the drill enters the NFRPCs. However, the bottom fiber layers are pushed out as the drill enters the bottom of the NFRPCs [6]. In general, inappropriate drilling causes delamination, resin erosion, and fiber breakout in composites. Low feed and high drilling speed are the optimum conditions for drilling to overcome these damages [15]. To avoid fretting in the clearance hole, the bolt must fit snugly in this joint. Interference fittings can cause composite delamination, thus using washers helps to protect the clearance hole [16].

During composite material bolt joining, the joint configuration has an impact on bolt joint strength [17, 18]. However, geometric parameter optimization of composite bolt joining failed horribly, resulting in overuse or underuse of joining geometry parameters. As a result, the joint became overweight or weak (unable to withstand the applied load). Hence, this study focuses to optimize joining geometry process parameters of bolt joint DPFRPC. The strength of bolt joint composite is highly influenced by joint geometry parameters such as composite thickness, type of lap, number of lap, number of bolt, hole diameter, W/D ratio, E/D ratio, and composite thickness [19]. Most research found that geometrical variables like W/D, E/D, and fiber orientation had an impact on the failure process [4, 20]. The optimum process parameters for strong single lap bolt joint DPFRPC are discovered in this study.

2 Materials and Methods

2.1 Manufacturing of the Composite

In this study, date palm fiber reinforced composite was manufactured using date palm fiber and polyester. The fiber was extracted from the rachis of date palm tree, from Bahir Dar, Ethiopia, due to its availability and better physical and mechanical properties. The fiber was extracted using a biological approach and then chemically treated with 1% NaOH alkali for 5 h to improve the fiber quality. Due to its simplicity, low cost, and ease of processing, the composite was manufactured utilizing the hand lay-up approach. The composite mold was made of wood with dimensions of 200 × 360 × 3.5 mm^3, as shown in Fig. 2(c). In this study the composite was made under 20%, 30% and 40% fiber loading with unidirectional orientation. The steps involved in fabricating DPFRPC are depicted on Fig. 2.


(a) (b)

(c) (d)

Fig. 2. DPFRPC making process; (a) rachis of date palm tree, (b) extracted DPF, (c) over its mold for composite making, (d) fabricated composite.

The composite was made by coating the mold with gel to provide a weak bond between the mold and the DPFRPC during demolding. Then a polyester was poured over the mold followed by putting the DPF over it, followed by rolling to remove air gaps. Finally, the layup was then covered with a concrete block capable of exerting 12.5 kPa pressure. After 5 h, the DPFRPC was demolded.

2.2 Bolt Joining of DPFRPC

Bolt joining was made after drilling DPFRPC specimen using drilling machine. To achieve a nice drilled hole, a fast drill speed, low feed, and drill diameter are needed [6]. In this study, the hole was made using 8 mm HSS drill bit under a rotational speed of 2000 RPM and feed of 45 mm/min. Finally, the bolt joint was made using M8 bolt. The bolt joint strength is highly affected by fiber orientation, E/D, and W/D [21]. Three joining parameters such as W/D (2.5, 3.5, and 4.5) and E/D (1.5, 2.5, and 3.5) were selected for this study as shown in Table 1 and Fig. 3. The specimen thickness and free length were kept constant at 3.5 and 130 mm, respectively.

Table 1. Parameters and levels of single lap bolt joint DPFRPC

No.	Factors	Levels		
		Level 1	Level 2	Level 3
1	Fiber orientation (°)	0/0	45/−45	0/90
2	Edge to diameter ratio (E/D)	1.5	2.5	3.5
3	Width to diameter ratio (W/D)	2.5	3.5	4.5

(a) (b) (c) (d)

Fig. 3. Bolt joint specimens (a) W/D, (b) E/D, (c) side, and (d) isometric view

2.3 Design of Experiment

The tensile properties of DPFRPC were characterized using fiber loadings of 20%, 30%, and 40% under unidirectional fiber orientations. After the tensile properties of DPFRPC were determined, an orthogonal array was used to identify the significant variables with the least number of trials possible, saving both time and money. Three factors with three levels were selected for single lap bolt joining of DPFRPC (E/D, W/D, and fiber orientation) as shown in. As a result, L_9 orthogonal array design of the experiment was adopted in Table 2. In order to ensure that all levels of all components are taken into account equally, L_9 orthogonal arrays were chosen.

Table 2. Experimental design of single lap bolt joint DPFRPC using L_9 orthogonal array

No.	Edge to diameter ratio (E/D)	Width to diameter ratio (W/D)	Fiber orientation (°)
1	1.5	2.5	0/0
2	1.5	3.5	45/−45
3	1.5	4.5	0/90
4	2.5	2.5	45/−45
5	2.5	3.5	0/90
6	2.5	4.5	0/0
7	3.5	2.5	0/90
8	3.5	3.5	0/0
9	3.5	4.5	45/−45

2.4 Tensile Test

The tensile properties of DPFRPC and single lap bolt joint DPFRPC were determined using UTM: WAW-600D tensile testing machine, as illustrated in Fig. 4. The WAW-600D is a computer-controlled hydraulic universal testing machine that uses hydraulic loading and computer displays for ease of use.

Fig. 4. Tensile test of single lap bolt joint DPFRPC using UTM: WAW-600D

2.5 Model Development and Optimization Using ANN-GA Approach

To determine the appropriate joining geometry parameters, artificial neural network (ANN) modeling and genetic algorism (GA) optimization method was used for this study, because this method is highly accurate modeling, predicting and optimizing tool, and the developed model can be used by other researchers for different targets [6, 22]. ANN takes input data, trains itself to detect patterns, and then predicts the output for a new collection of similar data by using the network shown in Fig. 5. ANN model was made using three layers; input layers, hidden layer, and output layers. The input layer contains the input process parameters (FO, E/D, W/D), whereas the output layer contains the failure load (Fl). The hidden layer is made up of many linked neurons determined through training, testing, and validation. The sum of inputs is transferred as output by each neuron's transfer function (activation function) and the weight value is assigned to each connection [22].

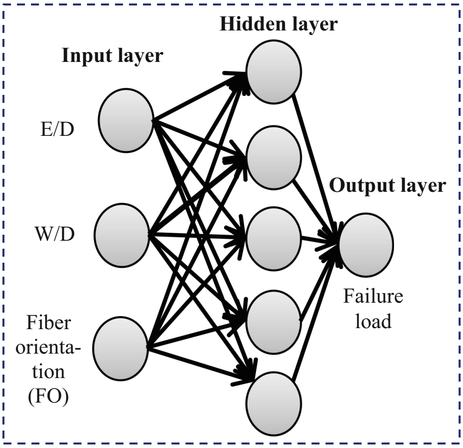


Fig. 5. ANN architectural model of bolt joint DPFRPC

In this study, GA was used to optimize the input space of the ANN model to obtain a set of optimum process parameter levels. Using the flow chart illustrated in Fig. 6, the fitness function of a previously created ANN model was used for GA to discover the optimal solutions. The constraints used for GA were E/D from 1.5 to 3.5, W/D from 2.5 to 4.5, and fiber orientation from 0 to 90 (degree). The GA parameters settings were

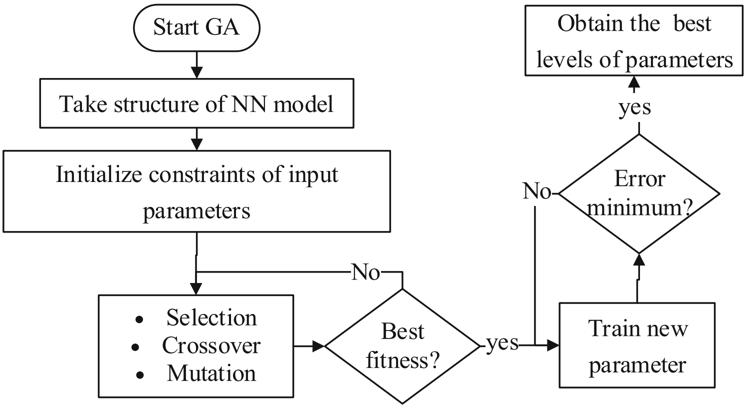


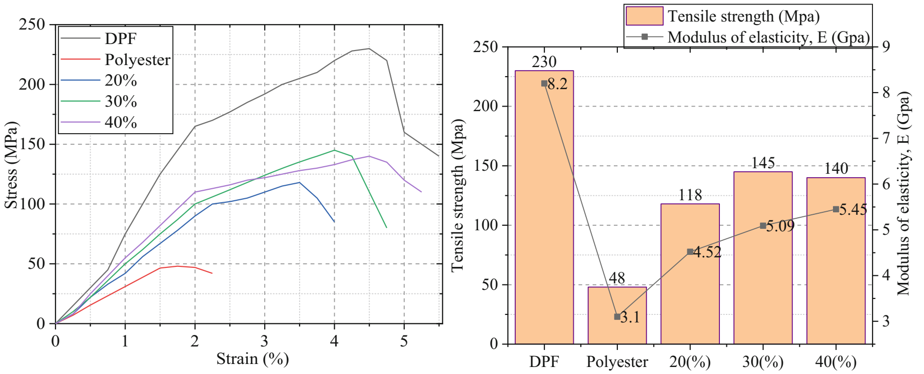
Fig. 6. GA model flow chart

determined based on past research and convergence. The GA-specific parameters are as follows: probability of crossover of 0.8, mutation rate of 0.01, population size of 50, and the number of generations over which GA evolved was 300.

3 Results and Discussions

3.1 Tensile Properties of DPFRPC

The tensile strength of DPF and polyester was determined experimentally before DPFRPC was made, and they were found to be 230 MPa and 45 MPa respectively. Ultimate tensile strength and stiffness of polyester resin were 79.13% and 62.2% lower than DPF respectively. The tensile properties of DPFRPC, which was made under 20%, 30%, and 40% fiber loading with unidirectional fiber orientation, was determined through tensile testing. From the experiment, the strongest DPFRPC was found at 30% fiber loading, 145 MPa, which was 58.6% lower than DPF and 66.8% higher than polyester matrix as shown in Fig. 7. There was 3.6 and 18.6% increase in tensile strength for 30% fiber loading compared to 40% and 20% fiber loading respectively. The tensile strength increases up to optimum fiber loading and starts to fall beyond that level of loading. This indicates that the DPFRPC joint has to be made using 30% fiber loading.



(a) (b)

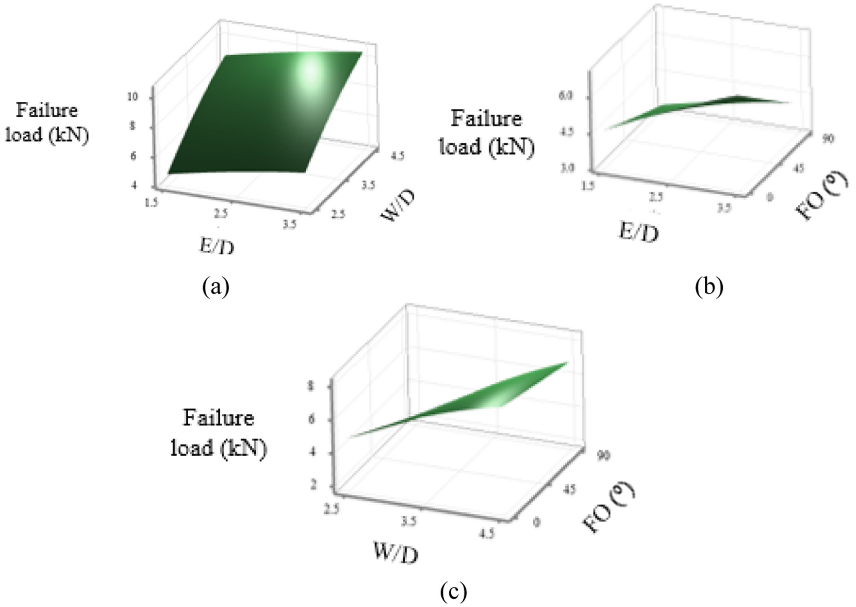
Fig. 7. Tensile properties (a) stress-strain curves (b) tensile strength and modulus of DPF, polyester, and DPFRPC with various DPF loadings.

3.2 Tensile Properties of Joined DPFRPC Subjected to Tensile Load

The experimental testing was carried out to analyze the effect of geometric joining variables of single lap bolted joint DPFRPC based on the design of experiments. From the result, different joint geometries show different load-carrying capacities. A maximum of 9.5 kN load caring capacity was found in experiment number 9 as shown in Table 3.

Table 3. Experimental results of single lap bolt joint DPFRPC

No.	E/D	W/D	Fiber orientation (°)	Failure load (kN)	Mode of failure
1	1.5	2.5	0/0	4.7	Net tension
2	1.5	3.5	45/−45	5.8	Net tension
3	1.5	4.5	0/90	7	Shear out
4	2.5	2.5	45/−45	4.8	Net tension
5	2.5	3.5	0/90	6	Composite failure
6	2.5	4.5	0/0	9.5	Cleavage tension
7	3.5	2.5	0/90	4	Net tension
8	3.5	3.5	0/0	9	Net tension
9	3.5	4.5	45/−45	9.45	Composite failure



(a)

(b)

(c)

Fig. 8. Surface plot of failure load vs (a) W/D and E/D, (b) E/D and fiber orientation, (c) W/D and fiber orientation of single lap bolt joint DPFRPC

The effect of input parameters with its load carrying capacity were related through surface plots as indicated in Fig. 8, shows the surface plots of responses of failure load with E/D, W/D and fiber orientation.

The highest load-carrying capacity was found at maximum E/D and W/D and minimum fiber orientation. An increase in E/D ratio and W/D ratio tends to increase load-carrying capacity (failure load), whereas the decreasing trend of failure load was observed with increased values of fiber orientation. This might be due to the fact that as then E/D and W/D increase, the joint area increases which help to sustain higher loads, whereas increased fiber orientation reduces the composite's strength, causing it to fail under a lesser load.

3.3 Failure Behavior of Joined DPFRPC

Post failure analysis of the fracture surfaces was examined after testing in terms of failure type (shear out, net tension, bearing). Figure 9 shows the failure single lap bolt joint of DPFRPC.

Fig. 9. The failure mechanisms of single lap bolt joint DPFRPC

According to the results of the experiment, net-tension failure occurs when the specimen's W/D ratio was too low (Fig. 9 experiment number 1, 2, 4,7, and 8). As the W/D ratio decreases, the side length decreases, reducing the force applied area. Shear-out failure was discovered along the shear-out plane on the hole boundary (Fig. 9 experiment number 3). It occurs when the E/D of the DPFRPC was small. On the other hand, composite failure (Fig. 9 experiment number 5 and 9) exists when the load acted on the specimen is beyond the load carrying capacity of DPFRPC. The combination of shear out and net tension (cleavage tension failure) exists, Fig. 9 experiment number 6, when E/D and W/D are nearly equal. The frequently existed failure was net tension, so the W/D has a significant effect than other parameters on the tensile strength of single lap bolt joining DPFRPC. Net tension and shear out can be avoided by increasing edge and width of specimen, whereas bearing exists in all types of failure before it fractures, and any change in the geometry will not be enough to avoid it.

3.4 ANN Modeling

The results of the experiments were used to develop an artificial neural network model. The developed ANN was trained with 9 sets of input (E/D, W/D, FO), and output (Fl) parameters emerged from the experiments conducted. The model was trained with two-thirds of the samples, and the remaining one-third was utilized for testing and validation with trainlm. The best ANN architecture for a single lap bolt joint DPFRPC was discovered after multiple attempts to be 3-6-1-1 (three neurons for the input layer, five neurons for the first hidden layer, one neuron for the second hidden layer, and one neuron for the output layer) as shown in Fig. 10. The activation functions for convergence in the first and second hidden layers, respectively, were the hyperbolic tangent and the linear transfer function.

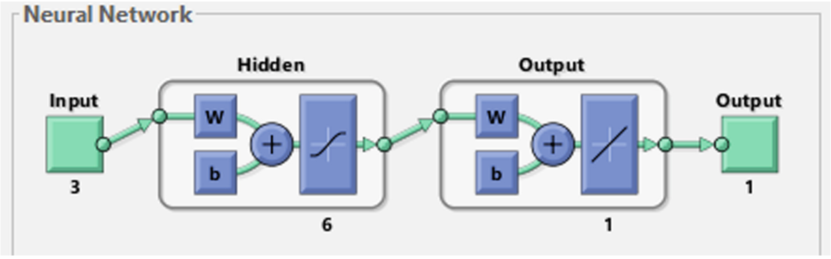


Fig. 10. Architecture of ANN model of single lap bolt joint DPFRPC

The performance of neural network training was conducted as shown in Fig. 11 curve, with the convergence to mean square error (MSE) of 0.045012 achieved after 1000 iterations or epochs. However, MSE reaches saturation in the second epoch itself. If an iteration increases beyond this, MSE begins to deviate from its optimal value.

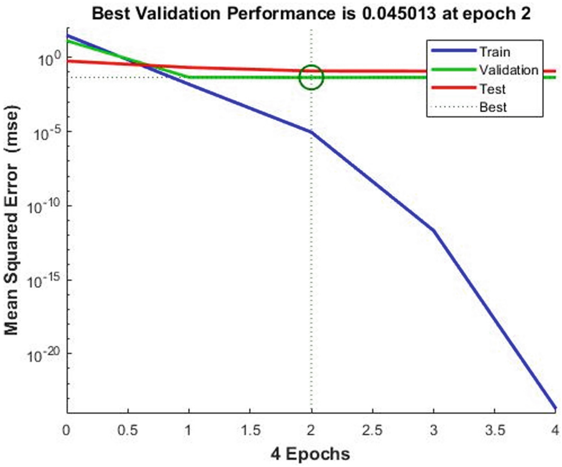


Fig. 11. Convergence of MSE during training of the ANN model

The network was validated by plotting the relationship between the network's outputs and the targets in a regression plot. The training, validation, and testing patterns were investigated in this regression plot as shown in Fig. 12. The correlation coefficient (R) for DPFRPC bolt joining was 0.996 in regression analysis, indicating a reasonable correlation between experimental and projected ANN response. The correlation coefficient (R) for single lap bolt joint DPFRPC was 0.996 in regression analysis, indicating a reasonable correlation between experimental and projected ANN response.

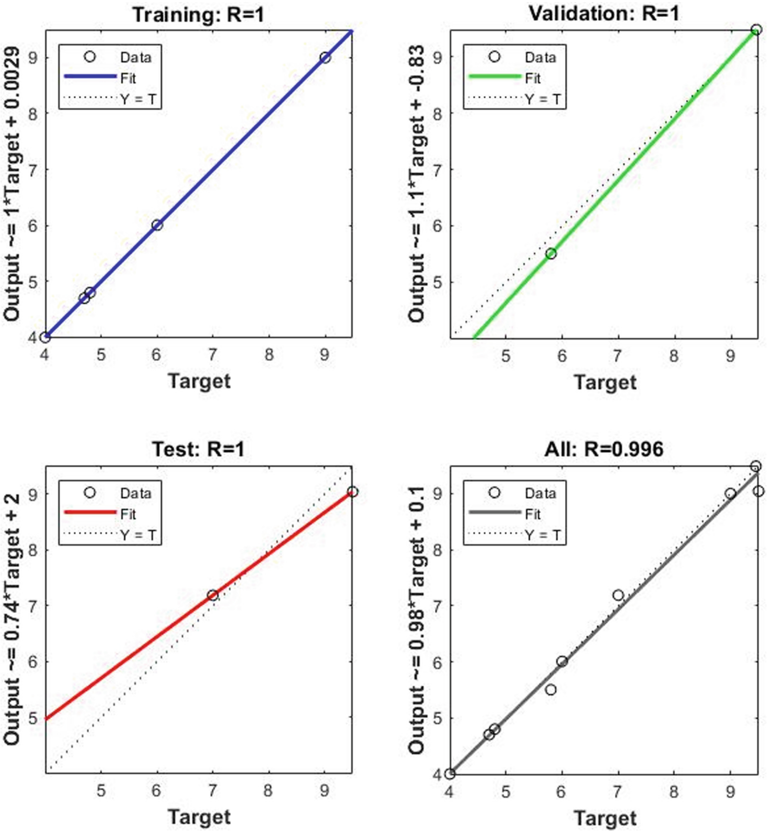


Fig. 12. ANN model simulation results in comparison with experimental results during training, validation, and testing.

There was relatively little variation between the experimental and predicted values of the ANN model, as shown in Fig. 13. From the analysis, the maximum error exists at experiment number six which was 0.4578%, and a minimum of zero error at experiment number eight. The error was within the acceptable range [22], so the model is accurate to relate the input and output parameters. The fitness function of this model can be used for genetic algorism to get the optimum input process parameters.

3.5 Optimization of Process Parameters by GA

The negative of the intended fitness function, obtained from ANN, was minimized because GA always minimizes the objective function. The GA parameters settings were determined based on convergence. The GA-specific parameters were 0.8 probability of crossover, 0.01% mutation rate, 50 population size, and 300 generations of evolution. With 56 generations, the mean fitness value of GA approaches the dominant fitness. According to GA, the best process parameters are 3.5 E/D, 4.5 W/D, and 56.4534° of

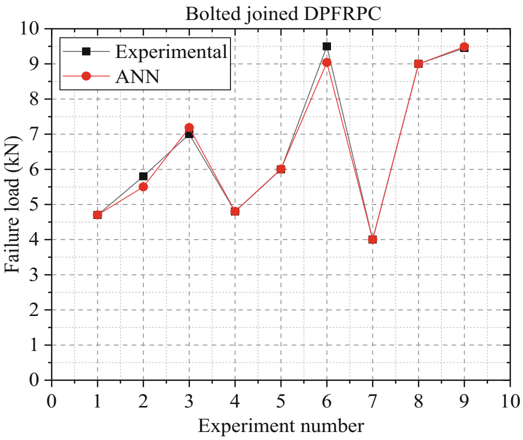


Fig. 13. Comparison of experimental and ANN predicted failure load values of single lap bolt joined DPFRPC

fiber orientation. The optimum output (failure load) was found to be 9.584 kN using these optimum settings, as predicted by ANN.

3.6 Confirmation Test

Based on the optimized ANN-GA result, a confirmation test was undertaken as shown in Table 4 to validate the model.

Table 4. Confirmation test result for bolt joined DPFRPC

Experiment	E/D	W/D	Fiber orientation (°)	Failure load (kN)
GA optimal solution	3.5	4.5	56.4534	9.584
Experimental solution	3.5	4.5	56.5	9.52
Error	–	–	–	0.064

The optimum process parameters levels found through GA were predicted with the developed ANN model. From the confirmation experiment, a maximum of 9.52 kN load-carrying capacity existed with an error of 0.064. So, the confirmation test output values agreed well with the ANN-GA model predicted values.

4 Conclusion

In this study, DPFRPC was made from DPF and polyester matrix through hand layup approach at the fiber loading of 20%, 30%, and 40% under unidirectional fiber orientation. A single lap bolt joining of DPFRPC was made using L9 orthogonal array design of experiments with three parameters and levels of E/D (1.5, 2.5, and 3.5), W/D (2.5, 3.5, and 4.5), and fiber orientation (0/0°, 45/−45°, and 0/90°). ANN model was developed to relate these input parameters and failure load through training, testing, and validation of the model. The best ANN architecture of single lap bolt joined DPFRPC was determined to be 3-6-1-1with an activation function of hyperbolic tangent and the linear transfer function in the first and second hidden layers, respectively. GA optimization technique was used by taking ANN model result as an input to get the optimum process parameters. Using this technique, the optimum process parameters of single lap bolt joint DPFRPC were, E/D of 3.5, W/D of 4.5, and fiber orientation of 56.5°, with a load-carrying capacity of 9.52 kN. An increase in E/D ratio and W/D ratio tends to increase load-carrying capacity (failure load), whereas the decreasing trend of failure load was observed with increased values of fiber orientation. This might be due to the fact that as then E/D and W/D increase, the joint area increases that helping to sustain higher loads, whereas increased fiber orientation reduces the composite's strength, causing it to fail under a lesser load.

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