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

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Abstract. Adhesive joining of composite materials is rapidly increasing in different engineering application areas such as aerospace, maritime and automotive, due to its potential for lightweight products. However, the use of adhesive joining for this purpose might lead to failure when a tensile load is acting on the composite. This work focus on the process parameters optimization of single lap adhesive joint Date palm fiber reinforced polyester composite (DPFRPC) to improve its joint strength. The study was conducted experimentally by making single-lap adhesive joining of DPFRPC under tensile testing. The key parameters influencing the adhesively joint's performance such as overlapping length (24, 40, and 56 mm), width (20, 28, and 36 mm), and adhesive thickness (0.5, 0.75, 1 mm) were studied using L_9 orthogonal array experimental design. Artificial neural network (ANN) modeling tool was utilized to relate input and output parameters. The best parameter combinations were found using a genetic algorithm (GA) optimization technique. Using this technique, the optimum parameters of single lap adhesive joint DPFRPC were, 56 mm overlapping length, 36 mm width, and 0.95 mm adhesive thickness, with a load carrying capacity of 9.48 kN.

Keywords: DPFRPC · Single lap · Adhesive joint · ANN · GA · Tensile strength

1 Introduction

Natural fiber reinforced composites (NFRPCs) materials are increasingly used in different engineering application areas such as aerospace, maritime and automotive industries, due to their lightweight and good specific mechanical properties [1–3]. From natural fibers, date palm fiber (DPF) specifically Phoenix dactyliferal, is the cheapest fiber with good physical and mechanical properties. All portions of the tree can be used to extract fibers [4]. This plant is founded abundantly in Bahir Dar, Ethiopia. But these date palms are fired and thrown as waste after cultivation, leads to environmental pollution and leads to illness [5]. Using this DPF as a composite material can solve these problems. When DPF and polyester are combined, gives a date palm fiber-reinforced composite (DPFRPC) with properties that are distinct from the ingredients [6–8].

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In many NFRPC application domains, NFRPCs are used in joined form for assembling purposes due to the increase in size and geometric complexity of structures made it impractical and expensive for the composite structure to be manufactured in a single shot continuous molding process [9]. This can be solved through adhesive joining, mechanical fastening, and a combination of the two [10]. The selection of the type of composite joining depends on the application area, the load needed to be transferred, and the weight of the joint [10, 11].

Adhesive joining of NFRPC involves the use of a variety of adhesives to attach the composite. This approach has a lengthy history, having been used in the aerospace sector in the 1970s and early 1980s [12]. Adhesive joining is widely accepted as a potential substitute for mechanical joints in modern industries (marine, automotive, aeronautical, construction, and so on) for different applications [13, 14]. With adhesive joining, there is no need to drill the composite; instead, alternative adhesives are used [15]. The type of adhesives utilized in the composite joining has an impact on its tensile strength. Epoxies, acrylics, polyester, urethanes, and other adhesives are used to assemble composites [16].

There are various types of adhesive joints, including single lap, double lap, scarf type, shim insert, strap type, stepped lap, and others. Single and double lap joints are the most popular and appropriate adhesive joining methods. Due to its simple geometry and great structural efficiency, single lap is employed more than double lap [12, 16]. This research focuses on a single lap joint for a uniform cross-section in the NFRPC application area as shown in Fig. 1.

Fig. 1. Single lap adhesive joining of composite material

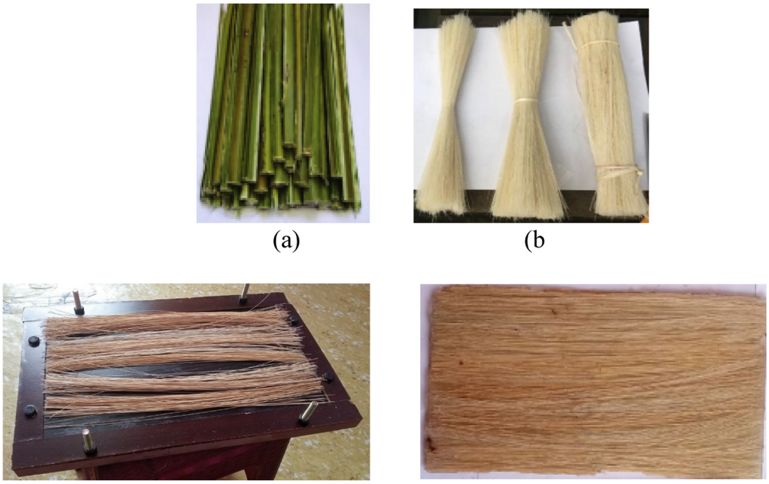
The joint configuration has an effect on adhesive joint quality during composite adhesive joining [12, 17]. However, geometric parameter optimization of the adhesive joining of composite had failed miserably, which leads to excessive or insufficient use of joining geometry parameters. This made the joined to be either overweighted or weak to resist the applied load. Nevertheless, optimizing overlap width, length, and adhesive thickness of joint was not studied adequately yet. Hence, this research work aims to optimize the joining geometry process parameters of adhesive joining of DPFRPC.

The joining geometry parameters in the adhesive joining process have an impact on the strength of a joined composite. Overlap length, width, adhesive thickness, and type of adhesive are the most important factors that help to achieve a high joint quality [18]. Overlap width is a more significant design feature than overlap length, even though joints with bigger surfaces have better strength. Due to stress concentration at the joint's ends, joint strength improves slightly with overlap length up to a limit, then remains constant. A joint with a long and narrow bond area is inferior to one with a short and wide bond area [18].

2 Materials and Methods

2.1 Manufacturing of Composites

Date palm fiber reinforced polyester composite (DPFRPC) 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. Hand lay-up technique was used to make the composite, due to its simplicity, with low-cost, easy processing. The composite mold was made of wood with dimensions of 200 × 360 × 3.5 mm^3, as shown in Fig. 2. In this study, the composite was made under 30% fiber loading with unidirectional orientation. Figure 2 represents the steps involved in the fabrication of DPFRPC.



(c) (d)

Fig. 2. DPF preparation 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 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 Adhesive Joining of DPFRPC

Following the fabrication of DPFRPC, single lap adhesive joining of DPFRPC was made. In this study polyester (parent matrix) that was used to make DPFRPC was also employed to make adhesive joining, due to its non-reactivity with the parent composite and helps to make comparable strength with the adherend. The polyester has been applied to the joining area of the specimens at the specified geometric area and adhesive thickness. Three joining parameters (overlap length, overlap width, and adhesive thickness) were considered with their corresponding levels as shown in Table 1. These variables were chosen based on how frequently they occurred and how they affected the tensile strength of adhesive joining. According to a review of the literature, the strength of an adhesively bonded composite is significantly influenced by the overlap length, overlap breadth, and adhesive thickness of the prior experiments [12, 19–22]. The specimen thickness and free length were 3.5 mm and 130 mm respectively. Figure 3 shows single-lap adhesive joint DPFRPC specimens.

Table 1. Parameters and levels of DPFRPC bolted joining

No.	Factors	Levels		
		Level 1	Level 2	Level 3
1	Overlap length, OL (mm)	24	40	56
2	Overlap width, OW (mm)	20	28	36
3	Adhesive thickness, t (mm)	0.5	0.75	1

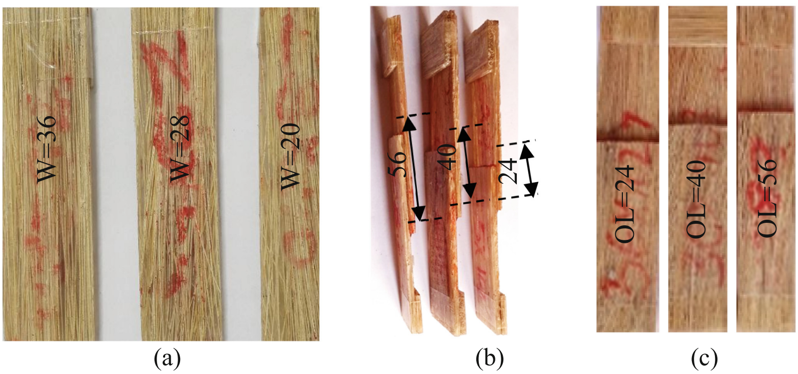


Fig. 3. Adhesive joining; (a) width of specimen, (b) overlap length side view of specimen, and (c) overlap length side view of the specimen

2.3 Design of Experiment

The tensile properties of DPFRP were characterized using fiber loadings of 30% 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 and levels were used as shown in Table 1, which are overlap length, width, and adhesive thickness. As a result, the L_9 orthogonal array was used, as shown in Table 2.

Table 2. Design of experiment using L_9 orthogonal array

No.	Overlap length	Overlap width	Adhesive thickness
1	24	20	0.5
2	24	28	0.75
3	24	36	1
4	40	20	0.75
5	40	28	1
6	40	36	0.5
7	56	20	1
8	56	28	0.5
9	56	36	0.75

2.4 Tensile Test

The tensile property of DPFRPC and single lap adhesive joint DPFRPC were determined using tensile testing machines. Tensile testing was carried out with a UTM: WAW-600D, as illustrated in Fig. 4.

Fig. 4. Tensile testing machine, UTM: WAW-600D

2.5 Model Development and Optimization Using ANN-GA Approach

The optimization technique helps to get a combination of levels of parameters of single lap adhesive joining of DPFRPC that will result in the best tensile load carrying capacity. For this study, artificial neural network (ANN) modeling and the genetic algorism (GA) optimization approach were utilized to identify the appropriate joining geometry parameters. Because it's highly accurate modeling, predicting, and optimizing tool and it can be used by other researchers for different targets. 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 (OL, OW, t), whereas the output layer contains the failure load (Fl). The hidden layer consists of many interconnected neurons that have been determined through training, testing, and validation. The sum of inputs is transferred as output by each neuron's transfer function (activation function). The weight value is assigned to each connection [23].

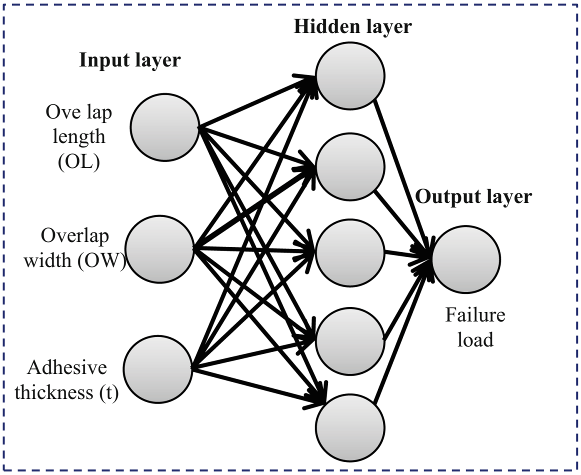


Fig. 5. ANN architectural model of adhesively joined DPFRPC

In this work, GA was employed to optimize the ANN model's input space to get a set of optimum levels of process parameters. The fitness function of previously developed ANN model was used for GA to determine the optimal solutions using the flow chart shown in Fig. 6. The constraints used for GA to optimize the process parameters were overlap length from 24 mm to 56 mm, overlap width from 20 mm to 36 mm, and adhesive thickness from 0.5 mm to 1 mm.

3 Results and Discussions

3.1 Tensile Properties of DPFRPC

The tensile properties of DPFRPC, which was made under 30% fiber loading with unidirectional fiber orientation, were determined through tensile testing. From the experiment, the ultimate tensile strength of DPFRPC was found to be 145 MPa as shown in Fig. 7.

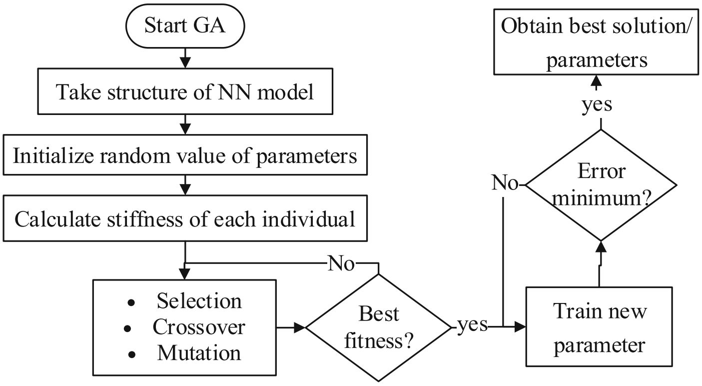


Fig. 6. GA model flow chart

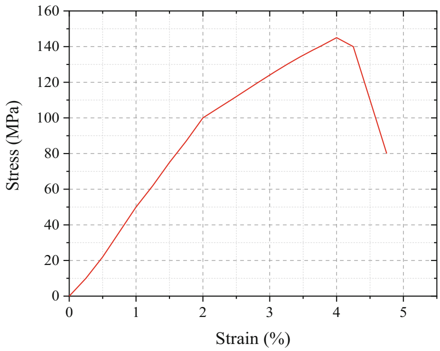


Fig. 7. Stress-strain curves DPFRPC

3.2 Tensile Properties of Joined DPFRPC Subjected to Tensile Load

Based on the design of experiments, experimental testing was conducted to examine the influence of geometric joining variables of single lap adhesive joint DPFRPC. From the result, different joint geometries show different load-carrying capacities. From the experiment, a maximum of 9.3 kN load caring capacity exists in experiment number 9 as shown in Table 3.

The effect of input parameters with its load carrying capacity was related through surface plots as shown in Fig. 8. Each plot has been made by taking the lowest levels of the remaining parameters.

The higher load carrying capacity was found at maximum overlap length and width because the bonding area increases with an increase in overlap width and length help to sustain higher loads and vice versa. On the other hand, maximum load carrying capability was found at medium adhesive layer thickness, because excessive adhesive layer thickness resulted in a thick bond line, which caused tiny cracks in the manufacturing due to vacancies.

Table 3. Experimental results of single lap adhesive joining of DPFRPC

No.	Overlap length (mm)	Overlap width (mm)	Adhesive thickness (mm)	Tensile failure load (kN)	Failure behavior
1	24	20	0.5	3.2	Thin layer cohesive
2	24	28	0.75	5.6	Fiber tear
3	24	36	1	6.5	Adhesive
4	40	20	0.75	5.2	Cohesive
5	40	28	1	5.7	Cohesive
6	40	36	0.5	7.2	Adhesive
7	56	20	1	4.9	Adhesive
8	56	28	0.5	7.8	Stock break
9	56	36	0.75	9.3	Stock break

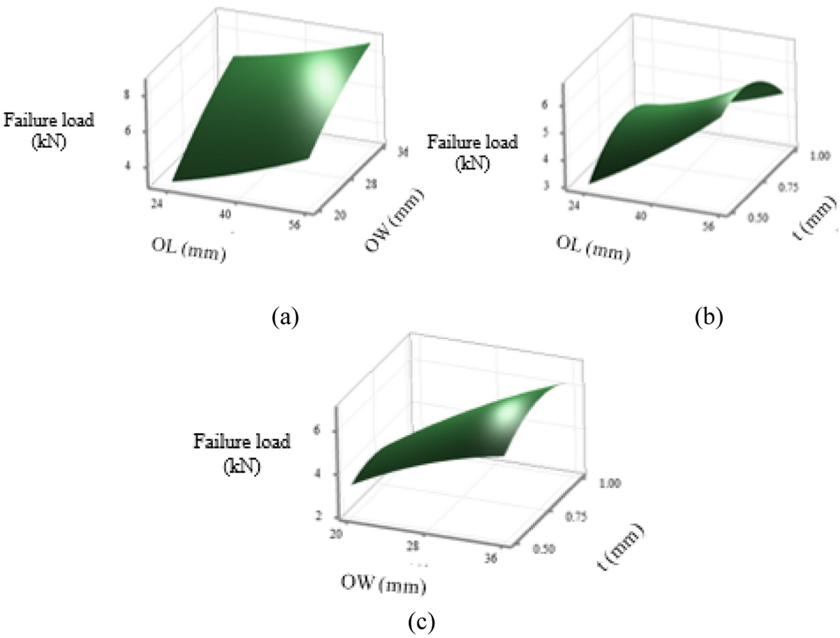


Fig. 8. Surface plot of failure load vs (a) OL and OW, (b) OL and t, (c) OW and t of single lap adhesive joint DPFRPC

3.3 Failure Behavior of Joined DPFRPC

The adhesive joint fails as the load applied over it exceeds its load-carrying capacity. Structural failure, cohesive failure, fiber-tear failure, and adhesive failure occurred, as shown in Fig. 9. Adhesive failure, Fig. 9 (3,6, and 7), as one side bonded more than the other side. Cohesive failure, Fig. 9 (4 and 5), where the adhesive thickness was at a higher level, the adhesive was too weak to resist the applied load. The stock failure, Fig. 9 (8 and 9), where the adherent fails rather than the joint and adhesive joint was strong. Fiber tear failure, Fig. 9 (1 and 2), due to the weak bond during DPFRPC manufacturing.

Fig. 9. Failure mechanism of adhesive joined DPFRPC

3.4 Modeling of ANN

The experimental findings were used to create an artificial neural network model. The developed ANN was trained with 9 sets of input (OL, OW, t), and output (Fl) parameters that emerged from the experiments conducted. Two-thirds of the samples were used for training, while the remaining one-third were used for testing and validation of the model using trainlm. After several trials, the best ANN model for single lap adhesive joint DPFRPC was determined to be 3-5-1-1 (three for input layer neurons, five for first hidden layer neurons, one for second hidden layer neuron, and one for output layer neuron) 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.

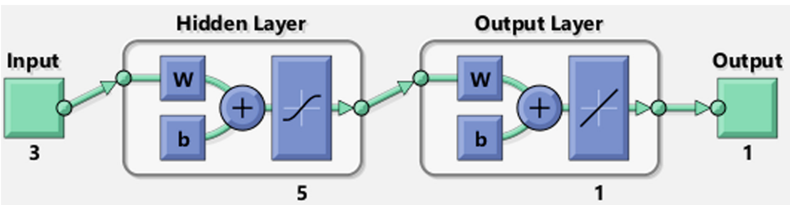


Fig. 10. Architecture of ANN model of single lap adhesive joint DPFRPC

The training performance curve for neural networks is depicted in Fig. 11 below, where adhesive joining ANN model convergence to mean square error (MSE) was determined to be 0.15049 made within 1000 epochs or iterations. However, MSE reaches saturation in the third iteration. Beyond this threshold, when an iteration increases, MSE begins to deviate from its optimal value.

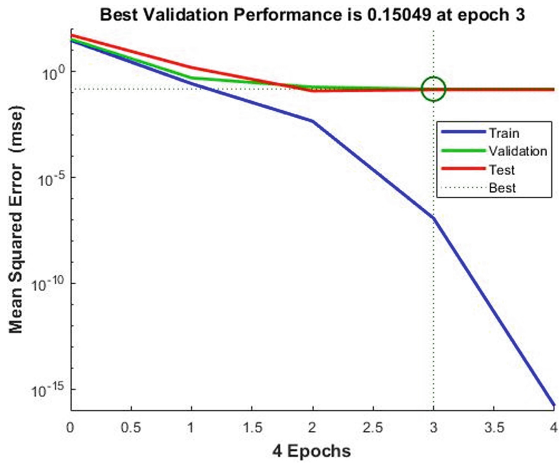


Fig. 11. Convergence of MSE during training of the ANN model

The training, validation, and testing patterns were investigated in the regression plot as shown in Fig. 12. The regression study revealed that the correlation coefficient (R) for single lap adhesive joint DPFRPC was 0.9896, implying that the experimental and expected responses are highly correlated.

There was relatively little variation between the experimental and predicted ANN model, as shown in Fig. 13, with a maximum error of 0.53427%.

3.5 Optimization of Process Parameters by GA

GA always seeks to minimize the objective function, so the negative of the proposed fitness function was minimized. Convergence was used to decide on the GA parameter setting. The GA-specific parameters were 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. After 50 generations there was no significant difference in fitness value, also there was a gradual decrease in population size after each generation. After 80 generations the optimal adhesive joining was designated from a pool of ANN/GA responses on the idea of the highest fitness value.

The optimum process condition of single lap adhesive joining obtained from the hybrid ANN/GA were overlap length of 56 mm, overlap width of 36 mm, and adhesive thickness of 0.982 mm. These optimum parameters were used by ANN to predict the optimum output (failure load), which was found to be 9.48 kN.

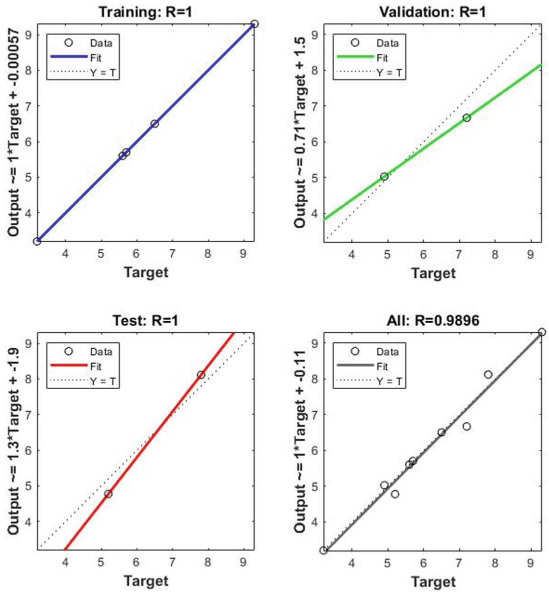


Fig. 12. ANN model simulation results in comparison with experimental results during training, validation, and testing.

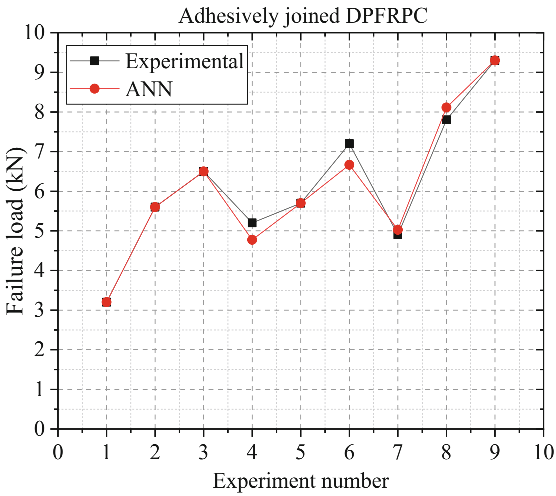


Fig. 13. Comparison of experimental and ANN predicted failure load values of adhesively joined DPFRPC

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. Although 0.982 mm of adhesive thickness provided the greatest strength, 0.95 mm of adhesive thickness was chosen for the precise manufacturing of the joint.

Table 4. Conformation test result single lap adhesive joint DPFRPC

Experiment	Overlap length (mm)	Overlap width (mm)	Adhesive thickness (mm)	Failure load (kN)
GA optimal solution	56	36	0.982	10.114
Experimental solution	56	36	0.95	9.48
Error	–	–	–	0.634

The optimum process parameter levels found through GA were predicted with the developed ANN model. From the confirmation experiment, a maximum of 9.48kN load carrying capacity obtained with an error of 0.634, indicates the confirmation test output values agreed well with the ANN-GA model predicted values. From the experimental study, the maximum tensile strength of unjointed DPFRPC was 145 MPa. Therefore, the adhesively joined DPFRPC showed less strength when it was compared to unjointed DPFRPC parent material.

4 Conclusion

In this study, DPFRPC was made from DPF and polyester matrix through hand layup approach at the fiber loading and orientation of 30% and $0/0^{o}$ respectively. A single lap adhesive joining of DPFRPC was made using L_9 orthogonal array design of experiments with three parameters and levels of overlapping length (24, 40, and 56 mm), width (20, 28, and 36 mm), and adhesive thickness (0.5, 0.75, 1 mm). 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 adhesively joined DPFRPC was determined to be 3-5-1-1 with 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 parameters. Using this technique, the optimum process parameters of single lap adhesive joint DPFRPC were, 56 mm overlapping length, 36 mm width, and 0.95 mm adhesive thickness, with a load carrying capacity of 9.48 kN. The test result indicates that, the increase in overlap length and overlap width the load carrying capacity of single lap adhesive joining of DPFRPC. However, it increases up to the optimum level of adhesive thickness and starts to fall beyond that point of thickness.

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