On the analysis of compressive failure load of single-lap bolted joint of green composites

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Abstract. In the present study, bamboo fiber reinforced polylactic acid (PLA) composites have been fabricated by hot compression molding using film stacking method. The compressive failure load behavior of single lap bolted joint of the developed composites has been experimentally investigated. The influence of the geometric parameters of mechanical bolted joint such as width to diameter ratio ($w/d$), edge to diameter ratio ($e/d$) and bolt fastening torque on the compressive failure load has been statistically analyzed. Taguchi’s analysis has been performed to find the optimum level of geometric parameters to obtain higher compressive failure load of the bolted joint. The $w/d$ and bolt fastening torque were found to be significant parameters influencing the compressive failure load of the bolted joint. The compressive failure load of the bolted joint is more at a higher value of $w/d$ and bolt fastening torque.

1. Introduction

The application of composites in different fields of engineering has increased because of their high specific strength, stiffness and ease of complex shape fabrication characteristics. In recent years, green composites composed of natural fiber and biodegradable polymer has emerged as an excellent material that replaced many synthetic fiber reinforced composites. The biodegradable characteristic makes these composites environmental friendly and eliminates the waste disposal problem [1]. Polymer composites are fabricated to near-net-shape in the primary manufacturing process. But in order to obtain the intricate structure, several composite components are fabricated separately and then they are joined to obtain the complete structure. However, joining of composites materials is not an easy task. High-stress concentration is developed in the joining area due to the anisotropic nature of the fibrous composites. The localized stresses at the joint are difficult to relieve because of the brittle nature of most of the composites and consequently limits the large displacement [2]. There are three basic methods available for joining of polymer composites: adhesive joining, mechanical fastening and fusion bonding. The primary means of joining of polymer composites is the mechanical fastening. In mechanical fastening, composites parts are joined by installing the bolt and nut in a hole. It is very important to design the bolted joint as this is the weakest region in the structure. Also, high stress localizes in and around the joint. The stress induced in a bolted joint is influenced by many factors such as the geometry of the joint, joint materials, bolt fastening torque etc. [3]. It has been revealed that the strength of a joint is affected by geometric variables such as width ($w$), edge distance ($e$), hole diameter ($d$) and laminate thickness ($t$) [4]. Several researchers have studied the failure behavior of
bolted joints of synthetic fiber polymer composites both numerically and experimentally by analyzing the distribution of stress. The fastener pull-through failure in carbon/epoxy composites was investigated both experimentally and numerically [5-6]. Arnold et al. [7] optimized the different parameters of mechanically fastened composite joints. The joint strength was predicted by developing a new semi-empirical technique. Choi and Chun [2] predicted the load during failure of a mechanically fastened composite joint. The authors have developed a new method of prediction called ‘failure area index’. The experimental values showed good agreement with the results obtained through numerical simulation. Chutima and Blackie [8] predicted the stress by developing 2-D finite element model in a joined specimen of carbon fiber reinforced composites. A 3-D finite element model was also developed to determine the strength and damage progression in joining of carbon fiber reinforced plastics [9-10] and graphite fiber reinforced plastics [11]. Experimental investigations on joining strength of carbon fiber reinforced plastics and glass fiber reinforced plastics were conducted for various laminate configurations, hole sizes, bolt tightening torque and geometric parameters (width, edge distance, hole diameter and laminate thickness) [12-13]. Senguttuvan and Lillymercy [14] experimentally determined the strength and mode of failure of riveted and bolted joint of glass fiber reinforced plastics by varying the number of rivet and bolt. However, a few works are available on joining behavior of green composites fastened by bolted joint. The green composites namely bamboo fiber reinforced polyactic acid (PLA) composites which is considered as an engineering material has been studied by many researchers by evaluating their mechanical properties [15-22], thermal properties [18,20], water resistance and interfacial adhesion characteristics [17] and crystallization behavior [22]. Fazita et al. [23] studied the recyclable and biodegradable behavior of bamboo/PLA composites. In the current study, the joining behavior of bamboo/PLA composites has been investigated by analyzing the compressive failure load. The bolt fastening torque and geometric parameters of bolted joint such as width to diameter ratio (w/d) and edge to diameter ratio (e/d) have been statistically analyzed and optimized to obtain the higher value of compressive failure load.

2. Materials and methods

2.1 Fabrication of composites

Bamboo fiber in woven form was purchased from Sri Lakshmi Group, Andhra Pradesh, India. PLA in pallets form was supplied by Natur Tec India Pvt. Ltd. The density of PLA is 1.24 g/cm$^3$. The melting temperature and glass transition temperature of PLA is 170°C and 58°C, respectively. The fabrication of the bamboo fiber reinforced PLA composites were carried out by film stacking method using hot compression. In order to remove the moisture, PLA pellets and the fibers were heated in an oven at 80°C for 4 hours. PLA films of 1.5 mm thickness were fabricated by hot compression of PLA pellets at 160°C. Initially, the pressure of 0.4 MPa was applied for 4 minutes and then increased to 3 MPa for another 2 minutes keeping the temperature constant. After allowed to cool the film for two hours under pressure, the film was removed from the mold. A total of four layers of fiber mats were stacked alternately between the PLA films. The stack of polymer films and fibers was compressed at a temperature of 180°C. Initially, 4 MPa pressure was applied for 8 minutes and then the pressure was increased to 6 MPa for 2 minutes. Composite was removed from the mold after 2 hours and allowed to cool. The thickness of the fabricated composite is 3 mm.

2.2 Experimentation

Table 1 shows the level of different parameters of bolted joint chosen for the purpose of investigation. The developed composites were cut as required size and hole was made with the help of vertical type milling machine under the dry condition, as shown in Figure 1(a). Drilling operations were carried out using a solid carbide drill bit (8-facet drill bit) of 8 mm in diameter (d) at 2000 RPM and 45 mm/min. The diameter of the bolt used for joining composite specimen was 8 mm with a pitch of 18 TPI. The bolt fastening torque was applied using a dedicated fixture mounted on a reaction type torque sensing device (Make: Syscon and Capacity: 100 kg-m). The torque sensing device with the developed fixture and the final bolted joined composite specimen is shown in Figure 1(b). The compressive failure load
of the bolted joint is obtained by Universal Testing Machine at a cross-head speed of 2 mm/min. A fixture was designed and developed in order to hold and apply the compressive load on the bolted joined specimen, as shown in Figure 2.

### Table 1. Levels of input process parameters

| Factors                        | Unit | Levels  |
|--------------------------------|------|---------|
| A: Width to diameter ratio (w/d) | -    | 2.5     |
|                                |      | 3.25    |
|                                |      | 4       |
| B: Edge to diameter ratio (e/d) | -    | 1.2     |
|                                |      | 1.8     |
|                                |      | 2.5     |
| C: Bolt fastening torque       | N-m  | 10      |
|                                |      | 15      |
|                                |      | 20      |

![Figure 1](image1.png) ![Figure 2](image2.png)

**Figure 1.** Experimental setup (a) drilling of composites and (b) applying bolt fastening torque

**Figure 2.** Measurement of compressive failure load

### 2.3 Design of experiments

It has been established that the bolt fastening torque and geometric variables of the bolted joint such as width to diameter ratio (w/d) and edge to diameter ratio (e/d) are important parameters that significantly affect the strength of bolted joint. In the current study, these three parameters at three different levels have been chosen to investigate the compressive failure load behavior of the composite joint. Orthogonal array $L_9$ was selected to carry out the experiments. The optimized parameters were found using Signal-to-Noise (S/N) ratio. The aim of the present study is to maximize the compressive failure load. Therefore, ‘larger the better’ quality characteristic was used for the compressive failure load. Analysis of variance (ANOVA) was also performed to obtain the relative significance of the process parameters affecting the compressive failure load. It also gives the percentage contribution of each process parameters on the compressive failure load.
3. Results and discussion
The experimental investigation was carried out to understand the effect of different geometric parameters of bolted joint on compressive failure load of the developed green composites. Table 2 presents the experimental layout and values of compressive failure load (both raw and calculated S/N ratios). The average values of raw data and S/N data are given in Table 3. The larger average values of raw data and S/N data at each level are shown in bold text. The main effect graphs of mean and S/N data are shown in Figure 3. Table 4 represents the optimal set of input parameters to obtain the maximum value of the compressive failure load. From the Taguchi’s analysis, it was found that the higher level of \(w/d\) (4), medium level of \(e/d\) (1.8) and a higher level of bolt fastening torque (20 N-m) gives a higher value of compressive failure load. Confirmation experiments were performed at the optimum level of input parameters obtained through Taguchi’s analysis. The compressive failure load was found within the confidence interval. The higher value of compressive failure load obtained at higher \(w/d\) and \(e/d\) is due to the increase in load carrying capacity of the joint with an increase in the width \((w)\) and edge distance \((e)\) keeping the diameter of the hole \((d)\) constant [24]. The load is transferred in a bolted joint by two means: bearing mode and friction mode. In bearing mode, the load is transferred in the joined specimens by the bolt that bears against the hole. It gives the idea of forces acting on the hole and deformation as well. The bearing strength of the joined composite specimen is more when the values of \(w/d\) and \(e/d\) are more. The load that can bear by the overlapping area is high at higher \(w\) and smaller \(d\) as the cross-sectional area of the overlapping section is more. The highly stressed composite specimen can press the bolt and the mode of failure changes from tension to bearing [4]. The failure load tends to be zero when the ratio of \(w/d\) is unity [25]. In the bearing mode, one of the joined plates is subjected to tension during the transfer of load. This generated tension is neutralized by the bearing stress developed in the bolt and hole. Mobilization of bearing stress occurs due to the slipping of the plates relative to each other. Therefore, failure will occur at the edge during slipping of the plates if the edge distance \((e)\) from the hole center is very small. Whereas the load is transferred in friction mode due to the induced tension between the plates as the force is applied during tightening of the bolt. It has been reported that the strength of the bolted joint is more when bolt fastening torque is high [26-27]. Higher fastening torque creates more friction between the bolt and specimen. This developed friction helps in releasing friction stress concentration in and around the bolted hole. Also, the washer that is used in bolted joint minimizes ply delamination. Hence, the specimen can carry the higher load when bolt fastening torque is high.

### Table 2. The experimental layout of \(L_9\) orthogonal array

| Sl. No. | A | B | C | Raw data | S/N data |
|--------|---|---|---|----------|----------|
| 1      | 1 | 1 | 1 | 1.745    | 4.8359   |
| 2      | 1 | 2 | 2 | 2.575    | 8.2155   |
| 3      | 1 | 3 | 3 | 2.820    | 9.0050   |
| 4      | 2 | 1 | 2 | 3.288    | 10.3386  |
| 5      | 2 | 2 | 3 | 3.690    | 11.3405  |
| 6      | 2 | 3 | 1 | 2.863    | 9.1364   |
| 7      | 3 | 1 | 3 | 4.430    | 12.9281  |
| 8      | 3 | 2 | 1 | 3.980    | 11.9977  |
| 9      | 3 | 3 | 2 | 4.388    | 12.8453  |

\(A, B, C\)- Process Parameters  
1, 2, 3- Levels of Process Parameters  
\(S/N\)- Signal-to-Noise Ratio
Table 3. Response for mean data and S/N data

| Data       | Parameter designation | Average values |
|------------|------------------------|-----------------|
|            |                        | Level 1 | Level 2 | Level 3 |
| Raw data   | A                      | 2.380   | 3.280   | 4.266   |
|            | B                      | 3.154   | 3.415   | 3.357   |
|            | C                      | 2.863   | 3.417   | 3.647   |
| S/N data   | A                      | 7.352   | 10.272  | 12.590  |
|            | B                      | 9.368   | 10.518  | 10.329  |
|            | C                      | 8.657   | 10.467  | 11.091  |

Figure 3. Main effect plot for means and S/N ratio

Table 4. Optimal setting of input parameters

| Response                              | Factor A                     | Factor B                   | Factor C                   |
|---------------------------------------|------------------------------|----------------------------|----------------------------|
| Compressive failure load (kN)         | Level 3 (w/d = 4)            | Level 2 (e/d = 1.8)        | Level 3 (20 N-m)           |

In Table 5, analysis of variance (ANOVA) of the experimental data for compressive failure load is presented. It is important to perform ANOVA to statistically analyze the influence of input parameters on the output response. From Table 5, it can be seen that the $F$ value for $w/d$ (factor A) is highest followed by bolt fastening torque (factor C) and $e/d$ (factor B). This indicates that the $w/d$ is the most significant model terms. It has the maximum influence on the compressive failure load. It was also observed in ANOVA that the $p$-value for $w/d$ and the bolt fastening torque is lower than 0.05 at 95% confidence interval. This indicates that the $w/d$ and bolt fastening torque are two significant parameters at a 95% confidence interval. $R^2$ value statically represents the closeness of the model to fit the data. The value of $R^2$ is 99.79%. This indicates that the fitness of the experimental data is quite satisfactory. The percentage contribution of $w/d$ is more followed by the bolt fastening torque to obtain the higher compressive failure load as can be seen in Figure 4.

Table 5. ANOVA for compressive failure load

| Source                             | DOF | Adj. SS | Adj. MS | F- Ratio | P-Value | % Contribution |
|------------------------------------|-----|---------|---------|----------|---------|----------------|
| A: $w/d$                           | 2   | 5.33913 | 2.66957 | 398.28   | 0.003*  | 82.910         |
| B: $e/d$                           | 2   | 0.11238 | 0.05619 | 8.38     | 0.107   | 1.745          |
| C: Bolt fastening torque           | 2   | 0.97469 | 0.48734 | 72.71    | 0.014*  | 15.135         |
| Residual Error                     | 2   | 0.01341 | 0.00670 | 0.107    | 0.208   | 0.208          |
| Total                              | 8   | 6.43961 |         |          |         | 100            |

DOF: Degree of Freedom
Adj. SS: Adjusted Sum of Square
Adj. MS: Adjusted Mean Sum of Square
*Significant at 95% Confidence Level ($R^2 = 99.79%$).
4. Conclusions
The concluding remarks drawn from the present experimental endeavor are presented below:

- The optimum values of input parameters to obtain the higher value of compressive failure load are the higher level of $w/d$ (4), medium level of $e/d$ (1.8) and a higher level of bolt fastening torque (20 N-m).
- The compressive failure load increases with an increase in $w/d$ and bolt fastening torque. At a high level of $w/d$ and bolt fastening torque, the specimen can transfer more load by means of bearing and friction mode. The compressive failure load increases with increase in $e/d$ up to a certain value and then it starts decreasing with further increase in $e/d$.
- The $w/d$ and bolt fastening torque were found to be the significant parameters to obtain the higher value of compressive failure load.
- The percentage contribution of $w/d$ is more followed by bolt fastening torque and $e/d$ to obtain a higher value of compressive failure load.

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