Dimensional Analysis for Predicting the Fracture Behavior of Particulate Polymer Composite Under the Effect of Impact Loading

Vinod Kushvaha and Aanchna Sharma

Abstract In the current study, a methodology of dimensional analysis based on Buckingham-pi theorem is presented to determine the dynamic fracture behavior of glass filled epoxy composites. Rod shaped glass fillers having an aspect ratio of 80 have been used to reinforce the epoxy matrix. These glass fillers were used in the volume fraction of 0%, 5%, 10% and 15%. Dynamic fracture toughness index for crack-opening mode (mode-I) is proposed to find out the fracture toughness of the Particulate Polymer Composites (PPCs) under different strain rate conditions of impact loading. The legitimacy of the proposed methodology is supported with the limited experimental results of dynamic fracture test which was conducted for varying filler concentration. The influence of various governing factors on the fracture toughness of the particulate polymer composites is also discussed and shear wave speed is found to have the most pronounced effect on the dynamic fracture toughness of the resulting composite.

Keywords Buckingham-pi theorem · Dynamic fracture toughness index · Dimensional analysis · Impact loading · Particulate polymer composite

1 Introduction

Composite materials have recently grown into the most appropriate alternative materials to be used by several industries like automobile, marine, aerospace, biomedical and electrical [5, 13, 20, 31, 48] etc. due to the combination of excellent properties such as high strength to weight ratio, corrosion resistance, chemical resistance, adhesion and dielectric properties [2, 10, 12, 24]. Depending upon the choice of reinforcement material, there are different types of composites that exist. Among these different types, Particulate Polymer Composites (PPCs) are easiest to manufacture and the most common type of composites [34, 36]. PPCs are made up of two or more constituent materials in which polymer serves as the matrix and some inorganic

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particles serve as the reinforcement. Mica, alumina, zirconia, silica etc. can be used to reinforce the polymer matrix. The fabrication of PPCs is also relatively cheaper along with the advantage of achieving tailored properties of the resulting composite by selecting the suitable filler reinforcement (in terms of type, size and shape), its volume fraction and the manufacturing process. Another aspect that makes PPCs one of the most appropriate materials for mechanical structural design is the macroscopic isotropy that these composites possess. The interfacial strength between the filler and the matrix is one of the key parameters that determine the overall performance of the resulting composite [9, 19, 37]. Hence, understanding the role of volume fraction of the filler and it's interfacial strength with the polymer matrix in determining the mechanical properties like strength, stiffness and toughness of the resulting PPC is critical for strategic engineering applications [21, 23, 41]. Investigating the mechanical behavior of composites corresponding to different design parameters and varying loading conditions experimentally is a very cumbersome and time consuming task. This has motivated researchers to look for alternative techniques in order to characterize the composite behavior with limited experimentation when subjected to different loading conditions [7, 8, 22, 38, 44, 45].

One such technique is the dimensional analysis, more precisely the Buckingham-π theorem which has been recognized as a very promising methodology for handling the intricacies of various physical concepts [4, 28]. This methodology offers certain process steps in order to develop compatible and meaningful dimensionless factors using the available set of parameters. The flexibility of the Buckingham-pi theorem lies in the fact that the characteristic relation between the parameters does not need to be known. This methodology has an ingrained physical basis because of which it has been extensively utilized in numerous engineering applications [11, 27]. The appropriate dependent and independent parameters obtained from physical experimentation are selected and using the technique of dimensional analysis, a functional relationship is established between the dimensionless quantities. Buckingham-π theorem has proven to be a very powerful scaling method and engrossed many scientists and engineers in the field for designing the practical problems. A numerical electroosmotic flow model was developed by making use of Buckingham-pi theorem in order to find a correlation between different physiochemical factors [32]. Another research group [6] performed an analysis of the roller bearings by means of Buckingham-pi theorem. A full scale test specimen of a simply supported beam made up of isotropic material was designed based on Buckingham-π theorem [46]. A research group [30] studied the characteristics of multiple bearing parameters when exposed to different temperature conditions and used dimensional analysis to determine the most significant factor affecting the bearing system. Another group [14] conducted a parametric study based on Buckingham-pi theorem to investigate the different system geometries of a composite slab.

In an attempt to solve a problem, analytical relations are usually established but it becomes very difficult to solve them as the number of parameters increases with increase in the intricacy of the problem. While in the laboratories, performing experiments that involve impact loading in order to study the fracture response of the composite materials, is very expensive and laborious [15, 16, 47]. In addition, it is a well-established fact that the fracture behavior of composites is non-linear in both pre- and post-crack initiation stages.

Owing to the potential of Buckingham-pi theorem to predict the material behavior, it has been implemented in various studies by different researchers. A group of researchers [39] came up with a model so as to find out the strain analogue to a very small biaxial loading condition. They derived conditions for the strain analogue to large biaxial loading by using Buckingham-pi theorem. Another research group [40] developed a mathematical model again by using Buckingham-pi theorem and studied the correlation between the different parameters influencing the tribological performance of the cutting tool. A study [17] was conducted to investigate the wear behavior of polymer composites reinforced with chopped fibres using the approach of dimensional analysis. A group of researchers [3] used the methodology of dimensional analysis to comprehend the micromechanics of particulate composites based on the macroscopic fracture toughness.

In this view, it is desirable to make use of dimensional analysis using the approach of Buckingham-pi theorem which is a powerful tool for better understanding of the fracture behavior under impact loading with limited experimentation. A lot of experimental work has been reported in the purview of dynamic fracture toughness of particulate polymer composites but the prediction of this dynamic behavior as a function of filler volume fraction is still ambiguous and requires attention.

Therefore the current work presents an integrated approach to illustrate the fracture behavior of particulate polymer composites under the effect of impact loading at varying strain rates. This approach is ingrained based on a similarity condition which is denoted as ‘dynamic fracture toughness index’. This index represents various factors like strain rate, material density, filler volume fraction, longitudinal wave speed and shear wave speed that can affect the crack initiation fracture toughness. This index is very useful for designing materials which have high resistance to impact load and hence can be utilized in numerous engineering applications.

The current study focuses on using Buckingham-pi theorem as a powerful tool of dimensional analysis in order to develop a model which will be used to evaluate the correlation between the crack-initiation fracture behavior and the dynamic fracture toughness index. This analysis utilizes the values of stress intensity factor analogue to different volume fractions of glass fillers obtained through lab experiments. Dynamic fracture toughness index is determined corresponding to different conditions of strain rate so as to widen the scope of utilizing the developed model to encounter various practical problems. Detailed methodology of the determination of this toughness index is reported elsewhere [18].

2 Experimental Procedure

In the current study, rod-shaped glass fillers of length 800 μm with a diameter of 10 μm (refer to Fig. 3) were used to reinforce the polymer matrix. Epoxy of low viscosity (Bisphenol-A) was used as the polymer matrix and glass fillers with an aspect ratio of 80 were used in a volume fraction of 0%, 5%, 10% and 15%. First of all, glass-filled epoxy sheets were cast and cured for seven days. Then these sheets were cut into rectangular test specimens of dimensions 60 mm × 30 mm × 9 mm. A notch of length, 6 mm was made at the middle of each test specimen with the help of a circular saw. The density, longitudinal wave speed and shear wave speed for neat epoxy composite (0% glass fillers) is 1146 kg/m^3, 2481 m/s and 1128 m/s respectively. The material properties of glass filled epoxy composite corresponding to different volume fraction of the glass fillers is given in Table 1. The detailed procedure of measuring those material properties is reported in another study [19].

The setup used to conduct the dynamic fracture test is shown in Fig. 1. The projectile impacted the test specimen at a velocity of around 16 m/s. Three different values of strain rate (3.7 s^{-1}, 10.7 s^{-1} and 40 s^{-1}) were used in the present study.

The in-plane deformation of the test specimen was measured by using the technique of Digital Image Correlation (DIC). The deformed and undeformed states of the test specimen were examined by means of a black and white speckled pattern on

Table 1 Material properties of glass filled epoxy composite

Particle type	Density, *D* (kg/m^3)	Longitudinal wave speed, C_L (m/s)	Shear wave speed, C_S (m/s)	Fiber volume fraction, V_f (%)
Rod shaped glass fillers	1226	2534	1188	5
	1285	2534	1243	10
	1375	2598	1286	15

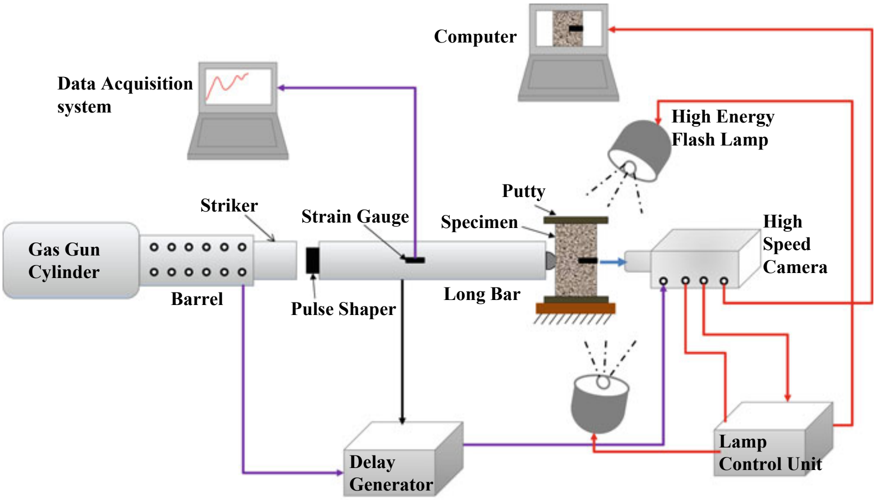


Fig. 1 Schematic of the setup used for dynamic fracture test [35]

the surface of the specimen. Further in order to extract the dynamic fracture toughness in terms of stress intensity factor, displacement fields obtained from Williams expressions were used. The detailed description of the experimental procedure is reported in a previous study [20].

When Buckingham-pi theorem is used to solve a problem having "x" variables and "y" dimensions then the variables can be reorganized into "x-y" independent dimensionless variables. This study deals with using Buckingham-pi theorem so as to establish the necessary functional relationships [1, 25, 33, 42, 43].

The functional relationship between the governing parameters which significantly affect the crack-opening mode (mode-I) dynamic fracture toughness under the effect of impact loading is given in Eq. (1).

$$K_I^d = f(\rho, C_s \text{ or } C_L, V_f, v, \gamma, \dot{\varepsilon}) \tag{1}$$

where K_I^d is the dynamic fracture toughness, ρ is the density of the material, v is the velocity of the crack, C_S is the shear wave speed, C_L is the longitudinal wave speed, γ is the Poisson ratio, V_f is the volume fraction of the glass fillers and, $\dot{\varepsilon}$ is the strain rate.

Using the Buckingham-pi theorem,

$$\pi_0 = f(\pi_1, \pi_2, \pi_3) \tag{2}$$

Out of the six governing parameters, C_S or C_L, $\dot{\varepsilon}$, ρ, γ, V_f and v, three parameters viz. $\dot{\varepsilon}$, v and ρ have independent dimensions. Therefore the dimensions of C_S or C_L, γ, and V_f are given as:

$$\pi_1 = [C_S \text{ or } C_L] = [v] \tag{3}$$

$$\pi_2 = \left[\gamma\right] = [1] \tag{4}$$

$$\pi_3 = [V\mathrm{f}] = [1] \tag{5}$$

$$\pi_0 = K_I^{index} = K_I^d \cdot (\dot{\varepsilon}^{0.5}/(\rho \cdot (C_L \text{ or } C_S)^{2.5}) \tag{6}$$

where, K_I^{index} is the dynamic fracture toughness index and $v^{index} = v/C_s$ or v/C_L is the crack velocity index.

3 Results and Discussion

In order to investigate the fracture behavior of particulate polymer composites, a mathematical relationship between the dynamic fracture toughness index and crack velocity index is presented using the approach of dimensional analysis.

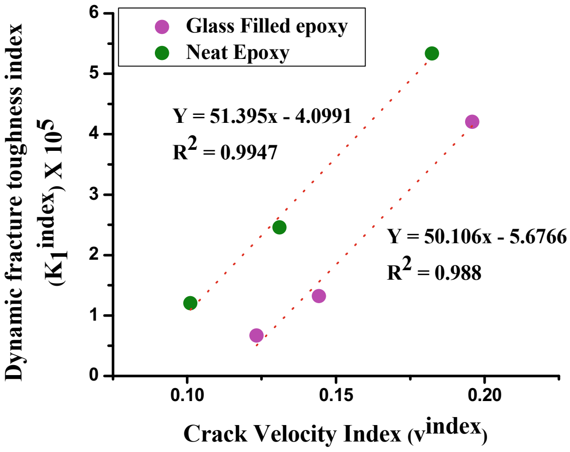
When a composite specimen is subjected to impact loading, the material experiences two different types of stress waves namely, longitudinal stress wave and shear stress wave [20]. Therefore the longitudinal and shear wave speed are included in the development of the mathematical relationship so as to account for the contribution of these stress waves in assessing the fracture toughness of the composite.

Figure 2a shows the variation in dynamic fracture toughness with respect to the crack velocity index for neat epoxy and glass-filled epoxy ($V_{\mathrm{f}} = 10\%$) composite. This graph is corresponding to three different strain rates and the longitudinal wave speed has been used as one of the parameters in the above mentioned mathematical model. Figure 2b represents the same variation but by utilizing shear wave speed in the developed model. The variation corresponding to both, the shear wave speed and longitudinal wave speed is found to be linear. Both the figures clearly show that the glass filled epoxy possesses a higher value of dynamic fracture toughness index compared to the neat epoxy composite. This is attributed to the fact that glass fillers improve the overall strength of the resulting composite.

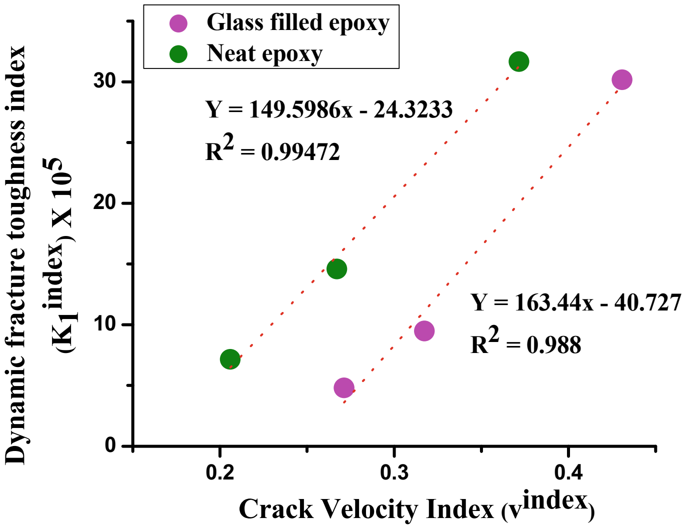
The slope in the first case corresponding to Fig. 2a is approximately 50 and the same corresponding to Fig. 2b is around 155, which clearly indicates that the influence of shear wave speed is much more pronounced on the fracture behavior of the composite compared to the longitudinal wave speed.

For better understanding of the failure mechanism due to the dynamic fracture, fractographic examination was done by means of scanning electron microscopy. Figure 3 shows the fractograph of the glass filled epoxy composite which clearly demonstrates the crack interaction with the filler reinforcement. Various failure modes like cracking of matrix, filler breakage and filler pullout are shown in Fig. 3. Each of these failure modes dissipate energy which consequently enhances the overall fracture toughness of the composite. At the crack tip, the presence of a substantial component of the in-plane shear resulted in filler matrix interface separation which further led to matrix cracking and hence matrix cracking was found to be the most dominating mode of failure. Similar filler-matrix interface separation as a failure mode has been reported for PPCs [26].

Figure 4 shows the relationship between the fracture toughness index and the crack velocity index at a constant strain rate, corresponding to the different filler volume fraction (5%, 10% and 15%). It was observed that increase in the concentration (volume fraction) of glass fillers, increases the dynamic fracture toughness of the composite. But this effect is not as much pronounced as it was due to the shear wave speed and this can be attributed to the fact that increase in the overall density and shear wave speed suppresses the effect of filler volume fraction. However, the contribution of filler concentration can be ascribed to increase the density of the resulting composite which ultimately makes the composite stiffer and stronger [29].



(a)



(b)

Fig. 2 Variation in dynamic fracture toughness index with respect to the crack velocity index **a** with longitudinal wave speed, **b** with shear wave speed

During the event of impact, shear stress wave interacts with the matrix and the fillers at a very high speed and this interaction directs the fracture behavior of the overall polymer composite. The filler pullout and breakage as shown in Fig. 3 is also attributed to the shear wave interaction with the fillers present in the glass filled epoxy composite.

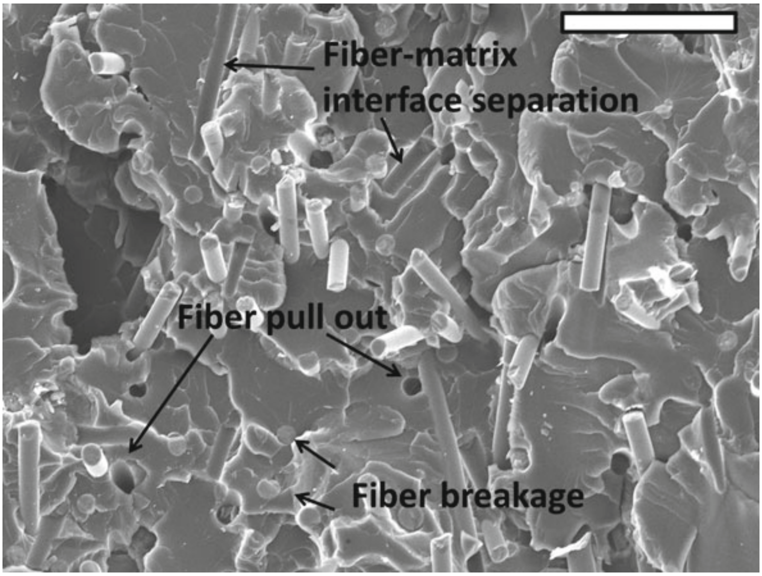


Fig. 3 Fractograph of rod-shaped glass-filled epoxy composite (scale bar = 100 μm)

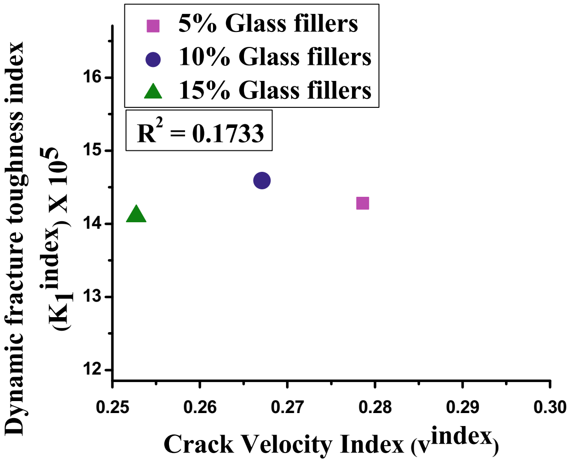


Fig. 4 Variation of dynamic fracture toughness index with respect to the crack velocity index for glass-filled epoxy

Finally, the developed functional relationship between the dynamic fracture toughness index and the crack velocity index was used to predict the fracture toughness for glass filled epoxy composites with three different volume fractions of the glass fillers (5%, 10% and 15%). These predicted results were compared with the experimental ones and the values were found to be close enough. Figure 5 shows

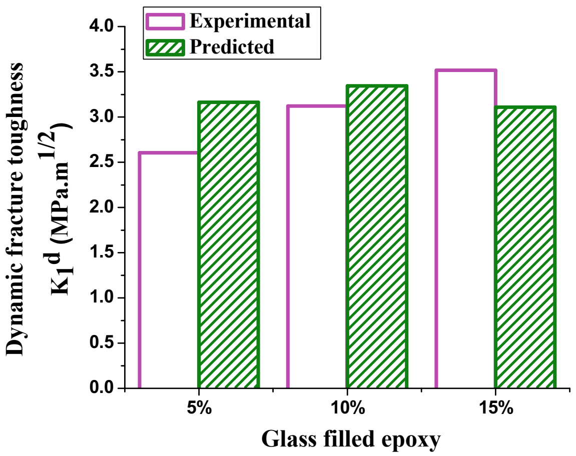


Fig. 5 Predicted versus experimental results for dynamic fracture toughness

a good agreement between the two results which encourages to further explore the possibility of using the proposed approach for predicting dynamic fracture toughness of PPCs with limited experimentation.

4 Conclusion and Future Perspective

The current study presents a technique to predict the dynamic fracture toughness of the glass filled epoxy composites under the effect of high strain rate impact loading by using dimensional analysis based on Buckingham pi-theorem. The legitimacy of the proposed methodology is supported with the limited experimental results of dynamic fracture test which was conducted for varying filler concentration. Shear wave speed is found to have the most significant effect on the dynamic fracture toughness of particulate polymer composite. The proposed dimensional analysis is found to be a very reliable and potential methodology to predict the dynamic fracture behavior of PPCs which is otherwise very tedious to investigate through multiple experiments. Furthermore, since the methodology has been observed to perform fairly efficiently, the same can be further extended to investigate the fracture behavior of composites using biofillers. This would assist in selection of a more efficient material and development of a robust composite with superior potential to resist fracture under dynamic loading.

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