Experimental Investigation and Numerical Simulation of Marble Dust Filled Aramid Fibre Reinforced Epoxy Composite for Wind Turbine Blade Application

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Abstract:

In this paper a series of marble dust filled aramid fibre reinforced epoxy matrix composites are fabricated using hand-layup techniqueby varying the marble dust content from 0wt% to 15wt% with an interval of 5wt%. Mechanical andfracture toughness behaviour of these composites are investigated. Inclusion of fillers alters the tensile, flexural, impact and inter-laminar shear strengths of aramid epoxy composites. Fracture toughness analysis in terms of stress intensity factor is done in Mode-I fracture for different crack lengths of 1mm, 3mm, and 5mm respectively and numerical simulation of the same is also done successfully by using finite element ANSYS model.

Introduction:

In order to obtain certain mechanical properties for a wind turbine blade application, it is important to find the changes in the performance characteristic of composite materials with changes in filler content under certain load conditions. These properties can further be increased by the addition of a filler material (as multi component system). Such type of system that contains matrix, fibre and filler is known as hybrid composite material. Filler materials reduce material cost and up to some extent increase mechanical properties and other properties like abrasion resistance, hardness and reduce shrinkage.

The performance of wind turbine blade importantly affects the performance of wind turbine system. For wind turbine blade application glass and carbon fibres are used as principle reinforcing material. Although glass and carbon both significantly improved the performance of turbine blade as carbon fibre reduced the weight of the blade with the same strength but the manufacturing cost of the turbine blade is also increased as compared to glass fibre. For minimum deformation the wind turbine blade material must be able to withstand load exerted by wind and gravitational forces with minimum weight. With this requirement hybrid composite is best suited for manufacturing of wind turbine

Aramid fibres have 5-10% better mechanical properties than other synthetic fibres, which are used in the applications as automobile, aircraft, marine, ropes, cables, and bulletproof vests [1]. Aramid fibres contain unmatched properties like high strength to weight ratio, stiffness, high fracture toughness and low density over other reinforcements [2].In Rajasthan the environmental pollution is increased due to the production of waste marble dust during cutting and machining of marble pieces, and if it is not used then it can create environmental issues and economic loss [3].In the form of particulate filler marble dust is used in wide range of areas and applications as ceramic, cement, dye, building material, glass, plastic and rubber industry, explosive, cleaning agents and in filtration and desulfurization processes [4].

Delamination is the one of the principal area of concern in laminated composite material for turbine blade application due to the expansion of moisture entrapped during the manufacture of composites, mismatch of engineering properties between adjacent layers, inter laminar shear stresses [7].The fracture toughness of granite powder filled jute epoxy composite is reported by M.J. Pawar that as the wt % of granite filler increases, fracture toughness increases, due to the restriction of crack propagation [8].Polymer composite materials are used in various applications, where it is more feasible to simulate the material properties before going for manufacturing and experimental analysis using one of the simulation models. In one of the recent research M. J. Pawar and Amar Patnaik investigated the fracture toughness of granite powder filled composite material for wind turbine blade application and granite powder filled jute epoxy composite for slurry jet erosion wear using ANSYS finite element code [9].

In view of the above study, mechanical properties of marble dust filled aramid fibre reinforced epoxy composites are calculated experimentally. Fracture toughness behaviour in terms of stress intensity factor in mode-I is also calculated experimentally and compared the experimental results with the finite element ANSYS model.

Experimental Procedures

Fabrication of composite

Thermoset epoxy resin (Hinpoxy C, density 1.20 gm/cc) is the matrix material in the present investigation and to fabricate composites aramid fibre (density 1.44 gm/cc, tensile modulus 105 GPa and tensile strength 3097 MPa) is taken as reinforcement in the epoxy matrix supplied by Hindoostan Composite Solutions. Marble dust powder (density 2.68 gm/cc and particle size 20 μm) is used as particulate filler in aramid fibre reinforced epoxy composite and is taken from CDOS (Centre for development of stones) Jaipur. Composites are prepared in four different percentages of marble dust powder (0wt%, 5wt%, 10wt%, 15wt% of marble dust) keeping the aramid fibre at constant percentage of 40wt%. Conventional hand-lay-up technique is used to fabricate composite plates followed by light compression moulding technique. For easy removal of the composite from the mould silicon spray known as releasing agent is used. A sliding roller is also used to remove entrapped air bubbles. For proper curing at room temperature castings are put under load for 24 h. For mechanical, dynamic mechanical and fracture analysis the specimens of suitable dimensions are cut. Table 1 shows the designation and composition of composites.

Table 1.

DESIGNATION AND COMPOSITION OF COMPOSITES

Composites	Compositions
EAM-1	Epoxy + Aramid Fibre (40wt%) + Marble dust (0wt%)
EAM-2	Epoxy + Aramid Fibre (40wt%) + Marble dust (5wt%)
EAM-3	Epoxy + Aramid Fibre (40wt%) + Marble dust (10wt%)
EAM-4	Epoxy + Aramid Fibre (40wt%) + Marble dust (15wt%)

Mechanical Characterization

Macro-hardness measurement is done using Rockwell hardness testing machine. A diamond cone indenter with an angle 120° between opposite faces is forced into the test material under a minor load usually of 10kgf and the applied major load F = 150kgf. Rockwell hardness number is noted using 'B' scale on dial indicator. The tensile strength (as per ASTM D3039-76), flexural strength (ASTM D2344-84) and inter-laminar shear strength (ASTM D2344-84) are determined using Universal Testing Machine (UTM) Instron 1195 with cross head speed of 10 mm/min. Impact tests are carried out on the sample specimens using impact testing machine (ASTM D 256). V-notch is produced on the sample specimen of 2 mm. The pendulum impact testing machine gives the notch impact strength of the sample by crushing the V-notched specimen with a pendulum hammer, measuring the spent energy, and relating it to the cross section of the specimen. The impact strength of the specimen is given by the impact energy in joules divided by the cross sectional area of the specimen at the notch.

Fracture Toughness Analysis

Fracture toughness of the sample specimen is calculated using the same UTM (Instron) in the form of stress intensity factor in mode-I (crack opening mode). As per ASTM D5045 the specimen geometry for mode-I is Single End Notch Bend (SENB) type. The test is performed in 3P-ENB test mode at cross head speed of 3 mm/min, with the ratio of (a/w) as 0.1, 0.3, 0.5, respectively. Where a is the crack length in mm and w is height of the specimen in mm. As per ASTM D5045 the following equations 1 and 2 are used to calculate the fracture toughness.

$$K_{IC} = \frac{F}{B.\sqrt{w}} * f\left(\frac{a}{w}\right) \; with \; 0 < \frac{a}{w} < 1 \qquad (1)$$

$$f\left(\frac{a}{w}\right) = 6\left(\frac{a}{w}\right)^{1/2} \left\{ \frac{[1.99-(a/w)(1-(a/w))(2.15-3.93(a/w)+2.7(a/w)^2)]}{(1+2(a/w))\left(1-(a/w)^{\frac{3}{2}}\right)} \right\} \qquad (2)$$

Where F is the maximum load, B is the width of the specimen, ɑ the crack length, w the height of the specimen.

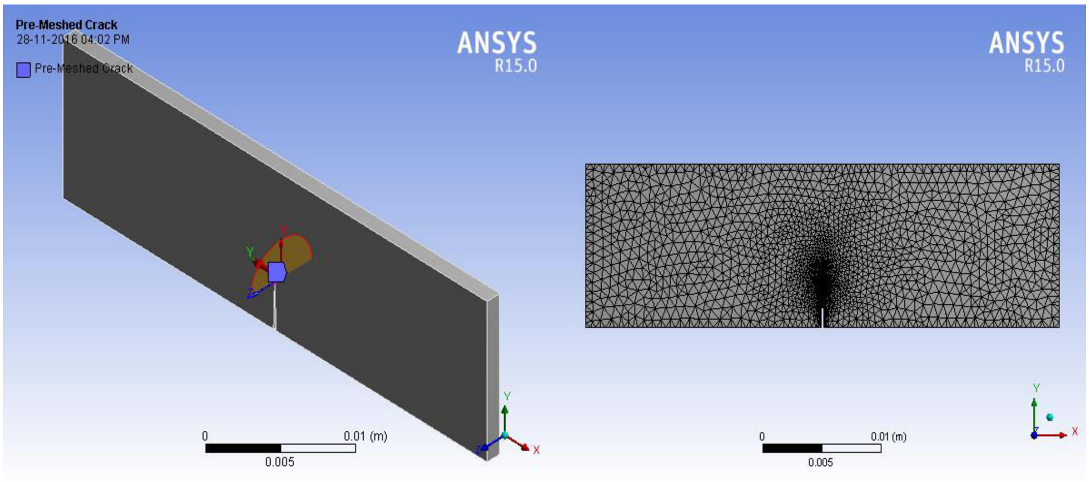

Fig. 1. Pre-meshed crack and type of mesh generated

Finally, numerical simulation of fracture toughness is done using ANSYS finite element code [10] of the unfilled and marble dust filled aramid fibre reinforced composites. To analyse the stress intensity factor in mode-I fracture, 3-D model is generated as per specimen geometry. The unfilled and marble powder filled aramid reinforced epoxy composite model is considered as homogeneous and isotropic material for analysis. Fig.1shows the pre-meshed crack and type of mesh generated. The interaction integral method [11] is used to calculate stress intensity factor of the composite model.

Results and Discussion

Density and Void Fraction

Theoretical densities calculated differ from experimentally measured values, because of the existence of voids and pores in the composite. Void fraction increases with increase in marble dust content from (5wt% to 15wt%)due to the irregular shape of filler. Experimental and theoretical densities of marble dust filled aramid fibre reinforced composites are shown in Table 2.

TABLE 2.

EXPERIMENTAL AND THEORETICAL DENSITIES OF MARBLE DUST FILLED ARAMID EPOXY COMPOSITES.

Composites	Experimental density (g/cc)	Theoretical density (g/cc)	Volume fraction of voids (%)
EAM-1(epoxy + 40wt% aramid fibre + 0wt% marble dust)	1.19	1.28	6.92
EAM-2(epoxy + 40wt% aramid fibre + 5wt% marble dust)	1.07	1.32	18.91
EAM-3(epoxy + 40wt% aramid fibre + 10wt% marble dust)	1.63	1.36	-19.80
EAM-4(epoxy + 40wt% aramid fibre + 15wt% marble dust)	0.95	1.41	32.15

Rockwell Hardness

With the inclusion of filler to the composite of 40wt%, hardness increases from 69 RHB to 93 RHB for filler content 5wt% to 10wt% but further decreases from 93 RHB to 77.83 RHB with increase in filler content to 15wt%. Addition of marble dust significantly increases hardness of composites up to certain limit (10wt% of marble dust), but further increase in filler content beyond 10wt% decreases mechanical properties due to the increase in water absorption and increase in porosity [12]. Fig.2 shows the comparison of different hardness values with respect to composites.

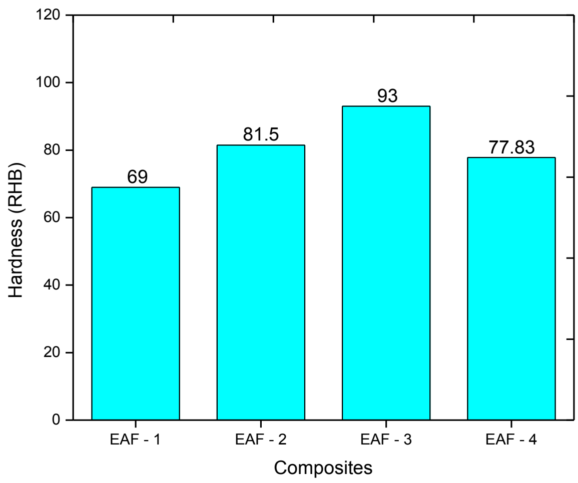

Fig. 2. Comparison of hardness with composites

Tensile Strength

Tensile strength of the composites decreases with increase in marble dust content form 0wt% to 15wt% as shown in Fig. 3. Aramid fibre composite with 40wt% fibre has tensile strength of 433.94 MPa, this value decreases to 258.03 MPa, 206.21 MPa, and 190.78 MPa with increase in filler content from 0wt% to 5wt%, 10wt%, and 15wt% respectively. Two reasons are responsible for reduction in tensile properties, the first possible reason is the weak interface between the filler particles and matrix; and the second possible reason is sharp edges of the asymmetrical shaped filler particles causes stress concentration.

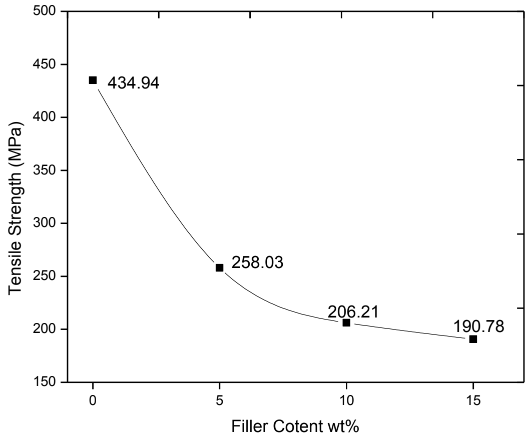

Fig. 3. Tensile strength vs filler content

Flexural and inter-laminar shear strength

It can be seen from Fig.4 that ILSS of composite with 0wt% decreases form 3.04 MPa to 2.85 MPa with the addition of marble dust up to 5wt %.With increase in marble dust content from 5wt% to 10 wt%, ILSS further decreases to 2.34 MPa. With increase in filler content up to 15 wt% leads to marginal increase in ILSS value to 2.96 MPa. So the possible reason of decrease in ILSS up to 10 wt% filler content is due to the weak interface.

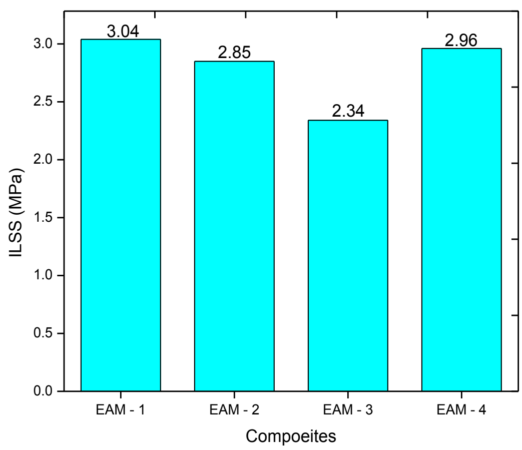

Fig. 4. Inter-laminar shear strength vs composites

Addition of marble dust improves the flexural strength of unfilled composite EAF-1 from 200.62 MPa to 258.89 MPa, 283.66 MPa and 290.1 MPa with increase in filler content from 0wt% to 5wt%, 10wt% and 15wt% respectively as shown in Fig. 5. This is due the increase in hardness of composite up to 10 wt% filler, but there is marginal increase in the flexural strength for filler content of 15wt% due to decrease in hardness value for 15wt% composite (EAF-4).

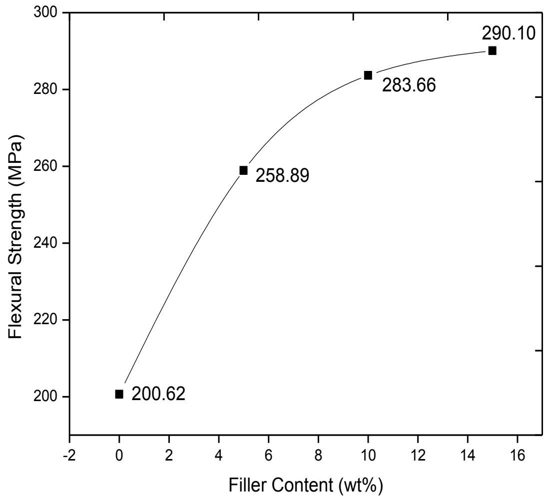

Fig. 5. Flexural strength vs filler content

Impact Strength

Impact behaviour of marble dust composites are shown in Fig. 6. There is continuous improvement in impact strength from 7 kJ/m^2 to 12 kJ/m^2 of composite with increase in filler content from 0wt% to 15wt%. Resistance to impact loading is the important property of hybrid polymer composites for many engineering applications.

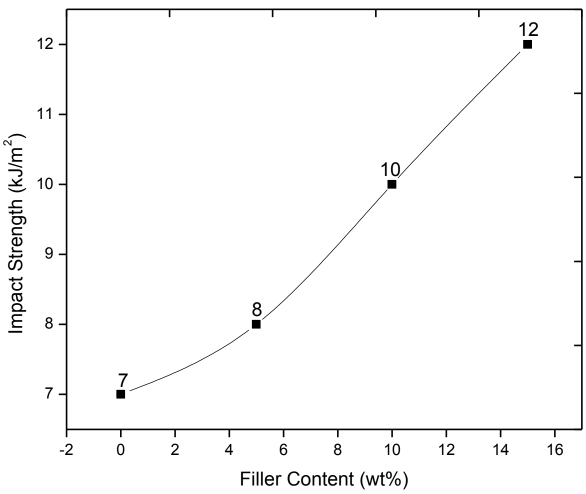

Fig. 6. Impact strength vs filler content

Fracture Toughness Analysis of marble dust filled aramid fibre reinforced epoxy composite.

Out of the several available methods to determine the fracture toughness of material, the critical stress intensity factor K_{IC} is used in this present study. Stress intensity factor of marble dust filled aramid epoxy composite is determined for different crack length to width ratio (a/W) of 0.1, 0.3 and 0.5, respectively. Fig.7 shows the variation of experimental values of the stress intensity factor with different a/W ratio. It is observed from the figure that stress intensity factor (K_{IC}) increases with increase in filler content up to 10wt%, further increase in content of particulate filler the value of K_{IC} decreases. This may be due to the more filler-filler interaction or filler –fibre interaction results in poor interfacial bond. The presence of marble dust filler in the composite divert the direction or path of crack that results in energy conservation. On further addition of marble dust up to 15wt% results in lower value of K_{IC} but still this value is greater than that of unfilled 40wt% fibre composite for all a/W ratios.

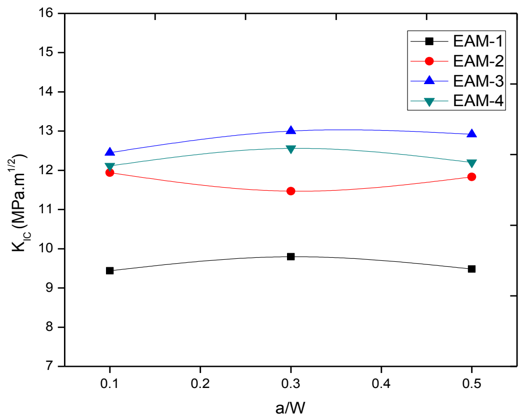

Fig. 7.Variation of stress intensity factor of marble dust filled aramid fibre reinforced epoxy composites

Numerical Simulation of Fracture toughness analysis of marble dust filled aramid reinforced epoxy composite

Numerical stress intensity factor of marble dust filled aramid composites with different crack lengths are tabulated in Table 3 and shown in Fig. 8. Numerical values for marble dust filled aramid composites are inferior to the experimental results of fracture toughness. This is due to the presence of marble dust particles in the track of crack front which causes modelling deficiency in the composite for inherent toughening mechanism. The lowest deviation (2.67%) is recorded with addition of 10wt% marble dust for a/W ratio of 0.5 and highest deviation (19.25%) is recorded with the addition of 15wt% marble dust for a/W ratio of 0.5.Fig.9(a) and(b) shows the equivalent von-misses stress contour and stress intensity factor (K_{IC}) established for marble dust filled aramid reinforced epoxy composite with filler content of 10wt% with a/W ratio as 0.5 along the crack front.

TABLE 3.

NUMERICAL STRESS INTENSITY FACTOR OF MARBLE DUST FILLED ARAMID COMPOSITES WITH DIFFERENT CRACK LENGTH

S. No.	**Compositions ↓ Crack length→**	**Stress intensity factor K_{IC} (MPa.m$^{1/2}$)**		
		1mm	**2mm**	**3mm**
1	EAM-1	9.78	9.08	9.46
2	EAM-2	10.47	10.16	10.23
3	EAM-3	12.00	11.56	12.58
4	EAM-4	10.85	10.67	10.23

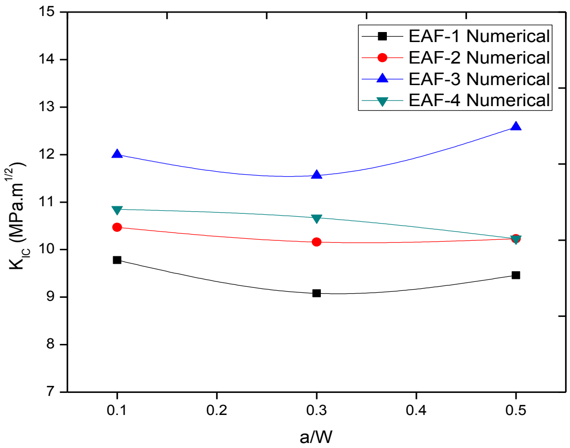

Fig. 8.Variation of numerical stress intensity factor of marble dust filled aramid epoxy composites.

The kidney shaped stress counters are observed at crack front in both figures. The location of the maximum stress intensity is different for different crack lengths. For a/W ratio of 0.1 the value of K_{IC} is higher towards the centre and the lower value is obtained towards the ends. The similar behaviour can be observed for a/W ratio of 0.3. For 0.5 a/W ratio K_{IC} is maximum towards the end. These results can be seen for other composites as well for all a/W ratios.

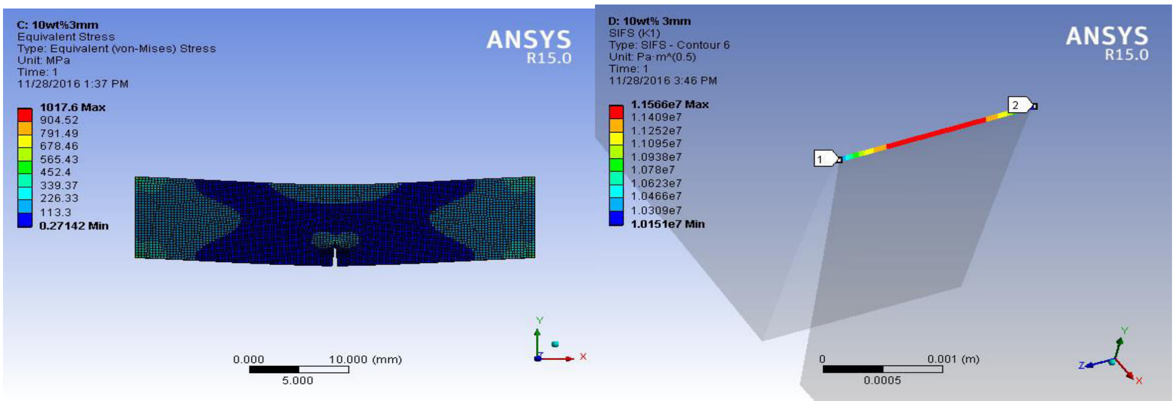

Fig. 9.(a) and(b) shows the equivalent von-misses stress contour and stress intensity factor (K_{IC}) with a/W ratio as 0.5 along the crack front

Conclusion

The present study on the experimental investigation on the effect of filler content on mechanical, dynamic mechanical, fracture toughness behaviour of aramid fibre reinforced epoxy composites leads to the following conclusions:

A series of marble dust filled aramid fibre reinforced epoxy matrix composites have been fabricated successfully.

The present study shows that inclusion of fillers alters the tensile, flexural, impact and inter-laminar shear strengths of aramid epoxy composites. Hardness, density and dynamic mechanical properties are also influenced by the incorporation of hard particulate fillers. Decrement in the value of tensile strength and increment in flexural strength is observed with addition of 15wt% marble dust. Hence there is a need to choose an appropriate filler material and its content for any specific application.

The fracture toughness of the aramid reinforced composite in the form of stress intensity factor (K_{IC}) has improved for all a/W ratios with addition of marble dust to the composite with filler content of 5wt%, 10wt%, and 15wt% respectively.

These composite can be recommended for the applications in wind turbine blades, automotive and aerospace applications

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