FLY ASH PARTICULATE REINFORCEMENT FOR PROPERTY ENHANCEMENT OF PU FOAM CORE SANDWICH COMPOSITES

Thesis submitted in partial fulfilment

for the award of degree

Doctor of Philosophy

by

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This is to certify that the work contained in the thesis titled ***"Fly Ash Particulate Reinforcement for Property Enhancement of PU Foam Core Sandwich Composites"*** by ***"ASHISH SINGH PARETA"*** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

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DECLARATION BY THE CANDIDATE

I ***"Ashish Singh Pareta"***, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***"Prof. S. K. Panda"*** from ***"July 2015*** to ***DECEMBER 2022"***, at the ***"DEPARTMENT OF MECHANICAL ENGINEERING"***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma.

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Abstract

The thesis strives to provide a road map to utilise the fly ash as a viable particulate reinforcement to polyurethane foam (PUF). The work also supports that the understanding the deformation mechanism of the components (face sheet and core) and sandwich composite under different loading condition i.e., compression, shear, bending and indentation, will gives perspective to design a sandwich composite.

In the current study, Silane coupling agent is employed to facilitate adhesion between an organic matrix and an inorganic filler. Thereafter, the shear test has been conducted on treated and untreated fly ash (FA) reinforced PUF core. The findings suggest that the stress carrying capacity of the silane treated FA-PUF outperform the untreated FA-PUF. Thus, the results depict that the FA as particulate reinforcement can be a sustainable option.

Now, the effect of varying FA wt. % inclusion in PUF core has been studies under compression and shear. ASTM C365/C365M and ASTM C273/C273M-16 has been used for compression and shear test respectively. The results shows that the polyurethane foam's shear modulus was improved from 14% to 39% depending on the weight percentage of fly ash inclusion to the neat PUF. While under compression the 20% FA-PUF's modulus is more than twice of the neat PUF.

Later, the glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) laminated face sheet has been fabricated and tested according to D3039/D3039M-17 for its tensile strength and modulus. The finding reports that the stiffness of the CFRP laminates is more than 3 time of GFRP.

Now, the sandwich composites were manufactured using GFRP/CFRP face sheet in combination with neat and FA-PUF core. The 3 Point test was conducted according to ASTM C393/C393M-16 to understand the deformation behaviour with varying wt. % of

FA-PUF on GFRP/CFRP sandwich composite. The results shows that CFRP sandwich composites performs better than the GFRP sandwich composites.

After performing the conventional mechanical testing, indentation resistance or response to localised stress is elaborately studied for both bare core and sandwich composite. At first the core alone is taken under consideration, here the effect of indenter geometry (flat-circular, hemispherical and conical) and inclusion of varying FA wt.% to PUF has been studied. The study shows the positive response to the reinforcement, owing to the fact, that the rigidity of the PUF increases with FA reinforcement. After indentation the cross-sectional cut of the damaged PUF core is analysed for the deformation behaviour and to corroborate the variation in performance due to reinforcement and indenter's geometry during indentation test.

At last, the indentation resistance of the sandwich composite has been conducted. The effect of face sheets, FA reinforcement and indenter's nose tip profile is taken under consideration. The CFRP sandwich composite performs better than the GFRP sandwich composite due to the stiff face sheet which provide better resistance against indentation. The study also concluded that the least resistance is offered in case of conical indenter and highest resistance offered by flat-circular indenter, while hemispherical lie in between these two indenters. The effect FA reinforced PUF core GFRP/CFRP sandwich composites are also analysed under different indenter's nose profile.

The improvement in mechanical properties of PUF foam core by employing a low-cost thermal power plant industry by-product fly ash seems to be an attractive alternative for future structural applications. This also has the advantage of reducing environmental hazards and corrosive pollution.

Acknowledgement

I express my sincere thanks and gratitude beyond words to my esteemed supervisor, Prof. S. K. Panda for his consistent help, encouragement, and valuable discussions during the entire period of my research work. It would not have been possible to complete the thesis without his utmost involvement and invaluable efforts. He motivated me to pursue research problem and the need for persistent effort to accomplish the goal. I am truly indebted to him.

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The world is going through some unprecedented times as the normal has been upended by the arrival of the deadly coronavirus pandemic. People across the globe are battling with Covid-19. Many who were locked at home like us were doing their part also by helping the people in many ways. But, others like doctors, soldiers, teachers, bank employee, office staff, railway employee, social volunteers etc. who are working outside to fulfil our requirements and taking care of the affected ones by risking their lives. I would like to thank them for their service towards humanity. Also, I would like to express my deepest condolences to those who lost their lives during this pandemic. Hope can always help pull people out of the most difficult of times. It is a powerful force and can prove to be a source of reassurance. Hence, I am immensely optimistic that very soon we will win this battle and lead a happy and fulfilling life ahead.

Last but not the least, I wish to thank my friends and the persons whose names have not been mentioned on this piece of paper for extending their cooperation directly or indirectly.

Ashish Singh Pareta

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Abbreviations

FA	Fly Ash
PU	Polyurethane
PUF	Polyurethane Foam
GFRP	Glass Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Polymer
MDI	Methylene Diphenyl Diisocyanate
SEM	Scanning Electron Microscope
QSI	Quasi-Static Indentation
ASTM	American Society for Testing and Materials

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Preface

Sandwich structured composites are a special class of composite materials are popular due to high specific strength and bending stiffness. Light in weight and buoyancy effect of these materials makes them especially suitable for use in aeronautical, space and marine applications. Sandwich panels are composite structural elements, consisting of two thin, stiff and strong face sheets separated by a core relatively thick layer of low-density and less stiff material. The face sheets are commonly made of steel, aluminium or laminate composite and the core material may be foam, honeycomb and balsa wood. The face sheet and the core material are bonded together with an adhesive to facilitate the load transfer mechanisms between the components. This particular layered composition creates a structural element with both high bending stiffness and bending strength. In order to bring solutions to the mass manufacturing, many developments and studies during these last years, were optimization of the mechanical performance/ density ratio. Indeed, the general concept of optimisation sandwich structures has been investigated and developed by many researchers. This study was undertaken with the same objective, but by having a strategy of optimization being focused more particularly on core material. Our step is to reconsider in its entirety core material and to propose a new concept of foam core which utilize Fly Ash (FA) as a practical particulate reinforcement which is an industrial waste from the power plant industry. This study aims to develop the new route of manufacturing the FA reinforced foam core with superior mechanical properties. The enhancement in properties has been corroborated by the different investigations under taken in the thesis work. First The bare core (neat and FA PUF) is tested under compression, shear and indentation loading. These foam cores are tested for its superior mechanical properties and change incurred to deformation mechanism after reinforcement. Then, these cores are combined with GFRP and CFRP face sheet. The sandwich composites are tested under 3-point bend test and quasi-static indentation (Flat-circular, hemispherical and conical). The variation in bending stiffness and indentation resistance with FA wt. % reinforcement to foam core sandwich composites have been studied elaborately.

Organization of thesis-: This thesis has been divided into seven chapters

Chapter-1 provides a brief introduction about composites and their applications. Design principle of the sandwich composite has been discussed in detail. Potential of core as a tool to increase the bending stiffness of the sandwich composite. This chapter also include failure mechanism of the sandwich composite. This chapter concludes with the aim and objective of the present investigation.

Chapter-2 presents how to couple inorganics filler material to organic matrix, particulate reinforcement affects the cell morphology, the effect of particulate shape and size on reinforcement characteristics. It also covers how the FA can be utilised in different ways and applications. This chapter discusses about the quasi-static indentation as a substitute of low velocity indentation to study the deformation sequence which equip the design engineers to design a high-performance sandwich structure.

Chapter-3 deals with details of materials used for the present investigation and experimental procedure of fabrication of sandwich components and sandwich composites. The experimental details of the physical and mechanical testing which are conducted according to ASTM standard of face sheet, foam core and sandwich panel has been included here. The SEM characterization to study the cellular morphology and the damage mechanism has been included.

Chapter-4 presents detailed discussion on the characterization of face sheet, core and sandwich composite. FA reinforced PUF core has been tested for its superior mechanical properties under shear test, GFRP and CFRP face sheets are tested for its tensile strength, and FA-PUF core GFRP/CFRP sandwich composite are tested under 3-point bend test. In this chapter it has been established that the FA inclusion to PUF core incurred positive mechanical properties when optimised.

Chapter-5 presents exclusive physical and mechanical testing of the neat and FA-PUF core. Effect of FA inclusion on PUF core density and compressive properties has been evaluated. The evaluation of indentation resistance of the PUF core with FA reinforcement in covered in this chapter. The effect of indenter's nose tip geometry on indentation resistance of the PUF core is also comprised here.

Chapter-6 focuses on the sandwich structure's responsiveness while considering the impact of GFRP and CFRP face sheets under quasi-static indentation. Fly ash loaded PUF core sandwich composites are investigated comprehensively. This study also investigates the response of sandwich composite changes with the change in nose profile geometry.

Chapter 7: presents the concluding remarks and future scope.

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