A Survey on Characterization of Glass Fiber Reinforced Polymer Composites

Mohan Kumar B¹ and Sathish S²

¹(Assistant Professor, Department of Mechanical Engg., Dr. Ambedkar Institute of Technology, Bengaluru, Karnataka, India)
²(Associate Professor, Department of Mechanical Engg., Dr. Ambedkar Institute of Technology, Bengaluru, Karnataka, India)

Abstract: Glass fiber reinforced polymer (GFRP) composites are a common type of fiber-reinforced plastic using glass fiber. Nowadays, GFRPs find application in many areas like electronics, aviation and automobile industries, to name a few. Glass fibers, which exist in various forms like rovings, chopped strands, yarns, fabrics and mats, have excellent properties like high strength, flexibility, stiffness and resistance to chemical harm. Each type of glass fiber has unique properties and is used for various applications in the form of polymer composites. In this paper, we present a survey on characterization of glass fiber reinforced polymer composites.

Keywords: GFRP, characterization, tensile test, impact test, analysis.

I. INTRODUCTION

Polymer composites find their way into thousands of new applications from sports products to aircraft, missile, spacecraft, marine applications and automobile components. Other uses include transportation, chemical equipment and machinery construction, electrical and electronic equipment, raining roofs and water storage tanks. A composite is a complex solid material, made by composing two or more dissimilar constituents in such a way that the resulting material is endowed with some superior and enhanced properties. Owing to these superior properties, polymer matrix hybrid composites find various applications in our daily life products. The lightweight, high strength to weight ratio, low cost and stiffness properties of composites have come to a long way in replacing the conventional materials such as steels, metals and wood. Composite materials are attractive because their combined material properties are not found in nature. Such materials are lightweight, have high strength and stiffness and are tailor made for specific products, thereby saving weight and reducing energy consumption needs. In fiber reinforced hybrid composites, the fibers serve as reinforcement by giving strength and stiffness to the structure while the matrix resin serves as the adhesive to bond the fibers in place so that suitable structural parts can be made. Fiber reinforced polymer matrix composites have better application in structural and non-structural areas as they have superior properties such as high specific stiffness and strength, good fatigue strength and damage tolerance, corrosion resistance, low density, low thermal expansion, non-magnetic properties, low energy consumption during fabrication and less production cost.

There are two types of fibers that are used in reinforcements namely, natural and synthetic fibers. A lot of work has been done in the field of composite materials these fibers. Fiber reinforced polymer (FRP) is one amongst the foremost materials necessary for engineering applications since it has very high stiffness, high strength, has good thermal and chemical properties, and, it is less expensive. In a Glass Fiber Reinforced Polymer (GFRP), Glass fibers (GF) are arranged in a random manner where they are flattened into sheet form (chopped strand mat), or woven into a fabric. The GFs are made up of different types of glasses relying upon the fiber glass usage. All the glasses contain silica/silicate, with different amounts of magnesium, oxides of calcium and typically chemical elements.

II. LITERATURE SURVEY

In [1] Haslan et.al studied laminate design of lightweight glass fibre reinforced epoxy composites for electrical transmission structure. In this paper, a laminate design of GFRP samples was stimulated using CompositeStar software to determine the mechanical strength and its reserve factor. The composite panels were varied in terms of fibre direction and it was designed to withstand a distributed load of 5kN service load in longitudinal (x-axis) and transverse (y-axis) direction on samples with thickness range between 4 to 4.2 mm. Through simulation, the authors observed that panels with fibre orientation in bi-direction and quasi-direction display a balanced strength along with an acceptable reserve factor in both x and y directions. A large difference of E value between the simulation and the experimental data were due to parameters that needed to be considered or regulated during the fabrication process. Due to some deficiencies, the fabricated samples exhibited a low modulus value compared to the simulated ones. The authors found that Rv value simulated from the CompositeStar software was reliable since it exhibited the same trend as compared to the experimental results.

http://indusedu.org

This work is licensed under a Creative Commons Attribution 4.0 International License
Thermal recycling and re-manufacturing of glass fibre thermosetting composites was studied by Fraisse et al. in [2]. A unidirectional glass fibre thermosetting composite laminate was manufactured and the impact of using thermally recycled glass fibre in re-manufactured composites was investigated. The matrix in one part of the laminate was burnt off to recover the glass fibres. These recycled glass fibres were used to manufacture a new composite laminate with the same fibre architecture as the pristine one. The recycled fibres were then used to re-manufacture a new composite laminate using the exact same processing conditions and involving minimal handling of the fibres in order to avoid damaging them. The two types of manufactured composite laminates were found to be of good quality, with low porosity content. The recycled glass fibres could not be packed as efficiently as the pristine fibres, which lead to a lower fibre volume fraction in the re-manufactured laminate. This was assumed to be due to electrostatic attraction between the recycled fibres where the sizing is removed. As far as the performance of the composites was concerned, the Young’s modulus was not significantly impacted by the recycling process. The recycled glass fibres were found to have a larger Young’s modulus than the pristine glass fibres, which theoretically also would lead to a larger Young’s modulus of the remanufactured laminate, in case of similar fibre volume fractions. The maximum stress of the remanufactured laminate showed a 90% reduction compared to the pristine laminate. Regarding the impact of the manufacturing process on the re-manufactured laminate, it was not possible to avoid it completely. It was shown that the brittle recycled fibres were breaking during the vacuum infusion process.

The mechanical properties of GFRP for structural applications was studied by Alexandre Landesmann et al. in [3]. The material samples used in this work were prepared in accordance to ABNT-NBR15708:2011 recommendations, extracted from web and flange parts of different geometries of one standard H-shaped GFRP single profile. A fairly extensive experimental program was carried out to cover both stiffness and strength structural characteristics of GFRP element comprising mechanical failures modes such as direct tension and compression, two-point flexural bending, pin-bearing pushed-out and interlaminar shear deformation. The results suggested that there was a clear difference, both qualitatively and quantitatively, on the nonlinear behavior of the stress-strain curves before, at and beyond the peak load, concerning the direct tension. The authors found that the resulting fibre contents exhibited a significant and direct influence on the mechanical behavior and the ultimate strengths of samples.

An experimental investigation on the durability of glassfibre-reinforced polymer composites containing nanocomposite was presented in [4] by Weiwen Li et al. In this study, 1.5wt% vinyl ester (VE)/organoclay and 2wt% epoxy (EP)/organoclay nanocomposites were prepared by an insitu polymerization method. The dispersion states of clay in the nanocomposites were studied by performing XRD analysis. GFRP composites were then fabricated with the prepared 1.5wt% VE/clay and 2.0wt% EP/clay nanocomposites to investigate the effects of a nanocomposite matrix on the durability of GFRP composites. Improvement in the durability of GFRP was achieved by adding montmorillonite composed of neat resin and organoclay nanocomposites, which forms a barrier to resist the permeation of water and chemicals into the matrix. Vinyl ester resin and epoxy resin were used as the matrix materials to prepare the nanocomposites. The dispersion states of montmorillonite in the resin were measured by XRD. Tensile tests were conducted to study the mechanical properties of GFRP. SEM was employed to characterize the degradation of the matrix, glass fibres, and the fibre matrix interface of GFRP. The 3.23 nm interlayer spacing measured by XRD indicates that polymer molecules intercalate into the interlayer space or even that some of the clay becomes exfoliated. The reductions in the tensile strength of VE-GFRP and VE/clay nano-GFRP immersed in water at 60°C were 22.48% and 21.38%, respectively. The tensile strength of the VE-GFRP and the VE/clay nano-GFRP immersed in alkaline solution was 47.91% and 57.24% respectively. The reductions in the tensile strength of EP-GFRP and EP/clay nano-GFRP immersed in water at 60°C were 10.24% and 18.74% respectively. The reductions in the tensile strength of EP-GFRP and EP/clay nano-GFRP immersed in alkaline solution were 32.02% and 38.41% respectively. The decline in the material properties of the VE/clay and EP/clay nano-GFRP composites was smaller than for VE-GFRP over the duration of the accelerated deterioration tests. According to the analysis of the relative influence of water and alkaline ions on the durability of the samples, the barrier formed by the addition of montmorillonite could resist the erosion induced by alkaline ions for up to 45 days. The durability of the nano-GFRP is thus improved by the addition of montmorillonite. VE/clay nano-GFRP tensile strength decreased by 22.48% (47.91%) after 60 days of immersion in water (alkaline solution), which, is greater than the decrease measured for EP/clay nano-GFRP. The authors conclude that EP/clay nano-GFRP has the best durability characteristics of the materials tested in this study. The authors also opined that if fabrication techniques for EP/clay nanocomposites could be optimized, the properties of EP/clay nano-GFRP can be improved even further.

In [5], Maksimov et al. have highlighted some techniques for modernization of technology and equipment for GFRP-rebar production. GFRP-rebar is widely used in the modern construction industry. The analysis of the manufacturing methods showed that the epoxy adhesive impregnation unit is imperfect. The impregnation is carried out by immersion of filaments in a pastepot or bending them around a rotary spool. After that, the devices are used to remove excess adhesive and guide rollers and form the rebar roving. The parts
contacting with adhesive must be regularly cleaned which makes the process low-efficient and increases financial and time costs. An open pastepot with the epoxy adhesive pollutes the air of the working area. Here the authors have proposed to change the impregnation unit and combine it with the device twisting filaments into a roving. It is necessary to dispense adhesive exactly from the nozzle to the place of the filaments connection. This will prevent harmful fumes from penetrating into the work area, maintain accurate adhesive dispensing, increase the production purity, and reduce the processing line and the cost. This construction doesn’t require large financial costs but can significantly improve the production efficiency. The proposed design of the equipment is realized with compact independent module that can be easily integrated into an existing manufacturing process. Modernization of the line can be at the same time with the repair work or scheduled maintenance. The module has the ability to install tracking systems work line automatic. The authors opine that a new technology using the proposed scheme dimensional directly dispensing adhesive during the formation of the ribbed reinforcement roving surface will provide highly efficient and cost effective materials.

Mechanical properties of GFRP Composites were studied by Wazery et al. [6]. In this research work, an E-glass fiber with random oriented reinforced polymer composite was developed by hand lay-up technique with varying fiber percentages (15%, 30%, 45%, and 60% by weight percentage). The influence of glass fiber percentage on the mechanical properties such as tensile strength, bending strength and impact strength was investigated. Hardness of composites was evaluated by using Brinell hardness tester. The results showed remarkable improvement in the mechanical properties of the fabricated composite with an increasing in the glass fiber contents. During this experimental investigation the authors concluded that successful fabrication of glass fiber with random oriented reinforced polyester composites with different fiber contents is possible and very cost effective by simple hand lay-up technique. It was found that the tensile strength varies from 28.25 MPa to 78.83 MPa, flexural strength varies from 44.65 MPa to 119.23 MPa and impact energy at room temperature varies from 3.5 Joules to 6.50 Joules with the variation in glass fiber percentage from 15wt.% to 60 wt.%. The hardness value was observed to increase from 31.5 BHN to 47 BHN when the resin reinforced by glass fibers was increased from 15 wt.% to 60 wt.%. Mechanical properties such as tensile strength and flexural, bending strength of polyester resin improved by a great extent due to the presence of glass fiber reinforcement.

Characterization of GFRP composite prepared by hand layup method was studied by Mahmood et al. [7]. In this work, glass fiber reinforced epoxy composites were fabricated. Epoxy resin was used as polymer matrix material and glass fiber was used as reinforcing material. The main focus of this work was to fabricate this composite material by the cheapest and easiest way. For this, hand layup method was used to fabricate glass fiber reinforced epoxy resin composites and TiO2 material was used as filler material. Six types of compositions were made with and without filler material keeping the glass fiber constant and changing the epoxy resin with respect to filler material addition. Mechanical properties such as tensile, impact, hardness, compression and flexural properties were investigated. Additionally, microscopic analysis was done. The experimental investigations show that without filler material the composites exhibit overall lower value in mechanical properties than with addition of filler material in the composites. Glass fiber reinforced epoxy resin composites were fabricated using hand layup method. Mechanical properties were investigated for different compositions of GFRP composites. Tensile, impact, hardness, compression and flexural values were higher for TiO2 filled composites than unfilled composites. Microscopic analysis was also done for GFRP composite. Investigations show that the composite having 15wt% TiO2 having maximum tensile strength of 290 MPa, 20wt% TiO2 having maximum impact strength of 0.1972 J/mm2, 20wt% TiO2 having maximum Rockwell hardness number of 71 HR, 25wt% TiO2 having maximum compression strength of 285 N/mm2, 20wt% TiO2 having maximum flexural strength of 2.70 KN/mm2. Experimental results showed that mechanical properties increase with addition of filler material. Filler material content having 20 wt% exhibited better mechanical properties than other filler contents or without filler content composites. The results indicated that with increasing filler material, mechanical strength increases but at certain composition, composite shows highest strength and then falls down. The surface of filler and without filler material and mixing conditions of the composites were studied with metallurgical microscope images. It is occurred due to non uniform mixing or void content or excessive use of filler material lead to high form of viscous mixture that lead to weak bonding between resin, filler and reinforcing material.

In [8], Jagannatha et al. discussed the mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites. In this work, the mechanical properties of carbon and glass fibers reinforced epoxy hybrid composite were studied. Vacuum bagging technique was adopted for fabrication of hybrid composite materials. The mechanical properties such as hardness, tensile strength, tensile modulus, ductility and peak load of hybrid composites were determined as per ASTM standards. Improvements in mechanical properties were observed as the fiber reinforcement content increased in the matrix material. Tensile properties were studied and breaking load was measured. The inclusion of carbon fiber mat reinforced polymeric composite significantly enhanced the ultimate tensile strength, yield strength and peak load of the composite. The ductility of carbon fiber reinforced composite was found to be higher than other composites.
In [9], Bino et al. discussed tensile, flexural and impact properties of GFRP matrix composites. The authors conducted several tests such as tensile test, flexural test and impact test. Experimental results showed that tensile strength increased by 19.30% gradually with more percentage of loading of silicon composite and hybrid composite. The flexural strength increased up to 14.22% gradually with an increase in percentage of silicon composite hybrid composite.

In [10], Arulkumar et al. have successfully fabricated Carbon-Sisal-Glass Fiber Reinforced composites with different fiber compositions. Mechanical properties of the various composite laminates such as tensile strength, flexural strength and impact strength was found to largely influenced by the fiber composition. In Tensile Test, CSCSC composition yielded the highest tensile strength then the other composition. In Flexural Test, CSCSC composition yielded the highest flexural strength and flexural modulus. In Impact Test, SGSOS composition yielded the highest impact energy in Joules and highest impact strength.

Mechanical properties of GFR epoxy composites were studied by Patil Deogonda et al. in [11]. In this paper, the authors describe the development and mechanical characterization of new polymer composites consisting of glass fibre reinforcement, epoxy resin and filler materials such as TiO$_2$ and ZnS. The newly developed composites are characterized for their mechanical properties. Experiments like tensile test, three point bending and impact test were conducted to find the significant influence of filler material on mechanical characteristics of GFRP composites. The tests results indicated that higher the filler material volume percentage greater the strength for both TiO$_2$ and ZnS filled glass epoxy composites. Also, ZnS filled composite showed more sustaining values than TiO$_2$ and tensile, bending and impact strength increases with addition of filler material. ZnS filled composite showed significantly good results than TiO$_2$ filled composites like more tensile load in comparison with unfilled and TiO$_2$ filled composites. Impact toughness notch across the laminates was found to be higher than that of along the notch. Impact toughness value for unfilled glass composite was more than filled composite. TiO$_2$ and ZnS filler materials make the material harder and brittle which is the reason for reduction in impact toughness value. ZnS filled composite shows significantly higher values than TiO$_2$ filled composites.

In [12], Yunfu Ou et al. studied the mechanical characterization of the tensile properties of GFRP composite under varying strain rates and temperatures. In this work, unidirectional GFRP was tested at four initial strain rates (25, 50, 100 and 200 s$^{-1}$) and six temperatures (25, 0, 25, 50, 75 and 100°C) on a servo-hydraulic high-rate testing system to investigate any possible effects on their mechanical properties and failure patterns. Meanwhile, for the sake of illuminating strain rate and temperature effect mechanisms, glass yarn samples were complementally tested at four different strain rates (40, 80, 120 and 160 s$^{-1}$) and varying temperatures (25, 50, 75 and 100°C) utilizing an Instron drop-weight impact system. In addition, quasi-static properties of GFRP and glass yarn were supplemented as references. The stress–strain responses at varying strain rates and elevated temperatures are discussed. A Weibull statistics model is used to quantify the degree of variability in tensile strength and to obtain Weibull parameters for engineering applications. This experimental study focuses on the tensile characterization and failure pattern of glass yarn and GFRP samples under different loading conditions. The strain rate and temperature effects on the mechanical properties and fracture morphologies were investigated and discussed comparatively. The authors concluded that there is an apparent dependence of the dynamics tensile properties of glass yarn and GFRP on the strain rate. For the glass yarn, tensile strength and toughness increase as much as 88.0% and 474.3% during a transition from quasi-static loading (1/600 s$^{-1}$) to dynamic loading (40 s$^{-1}$), but toughness decreases about 10.2% when the strain rate changes from 120 to 160 s$^{-1}$ due to the diminution of strain. For GFRP, the tensile strength linearly increases nearly 49.1% over the strain rate range of 1/600–200 s$^{-1}$, and toughness increases remarkably (about 109.7%) during a transition from quasi-static loading (1/600 s$^{-1}$) to dynamic loading (25 s$^{-1}$). The mechanical properties of glass yarn and GFRP were also dependent on the temperature. For glass yarn, tensile strength and toughness decreased nearly 25.3% and 31.1% when temperature increases from 25 to 75 °C. However, when heated to 100°C, tensile strength and toughness of glass yarn rebound due to the augment of frictional force between fibers. For GFRP, tensile strength shows almost no change (within 3%) when temperature increases from 25 to 50°C, but decreases sharply (about 18.9%) over the temperature range of 50–100°C because of the softening of the resin matrix when Tg of epoxy resin is reached.

In [13], Guangfa Gao et al. studied the mechanical properties of woven glass-fiber reinforced polymer composites. The mechanical properties of a woven glass fiber-reinforced polymer composite were investigated in quasi-static compression and tension tests. The composite being regarded as a transversely isotropic material, compression tests in the normal and tangent directions and tension tests in the tangent direction were conducted. The investigation showed that the composite is an elasto-brittle material, and its compressive failure strength is significantly greater than its tensile strength. A positive strain rate effect on the compressive behavior in the normal direction was discovered. The experimental results show that failure stresses and strains of the composite in the normal direction are all significantly greater than those in the tangent direction at different strain rates. For the polymer, shear failure is the dominant failure mode in quasi-static uniaxial compressive loading. In the process of compressive loading in normal direction, the interaction strengthened gradually.
fiber with greater tensile strength contributed more to compressive strength in the normal direction than that in the tangent direction. However, in the elastic stage, the deformation was so small that the polymer played a dominant role in this process. Thus, the Young’s moduli of the composites in the two directions were similar.

In [14], Guanghui Li et al. studied the fatigue behavior of glass GFRP bars after elevated temperatures exposure. For experimental purposes, a total of 105 GFRP bars were conducted for testing. The specimens were exposed to heating regimes of 100, 150, 200, 250, 300 and 350°C for a period of 0, 1 or 2 h. The GFRP bars were tested with different times of cyclic load after elevated temperatures exposure. The results showed that the tensile strength and elastic modulus of GFRP bars decreased with the increase of elevated temperature and holding time, and the tensile strength of GFRP bars decreased (obviously) by 19.5% when the temperature reached 250°C. Within the test temperature range, the tensile strength of GFRP bars decreases at most by 28.0%.

It was observed that the cyclic load accelerated the degradation of GFRP bars after elevated temperature exposure. The coupling of elevated temperature and holding time enhanced the degradation effect of cyclic load on GFRP bars. The tensile strength of GFRP bars after elevated temperatures exposure at 350°C under cyclic load reduced by 50.5% compared with that at room temperature and by 36.3%. In addition, the elastic modulus of GFRP bars after elevated temperatures exposure at 350°C under cyclic load reduced by 17.6% compared with that at room temperature and by 6.0% compared with that after exposing at 350°C without cyclic load.

Khan et al. [15] studied the low velocity impact of filament-wound GFRP reinforced composite pipes. Low velocity single-bounce impact tests were conducted on filament-wound glass fiber reinforced/vinylester and glass fiber reinforced/epoxy composite pipes. An instrumented drop weight testing system was used for the impact testing. The tests were performed on 300 mm long sections of 150 mm diameter pipes having 6 mm wall thickness. The impact energy required to just initiate the damage in glass fiber reinforced/epoxy pipes was found to be larger than the energy needed for glass fiber reinforced/vinylester pipe. The load-time curves also revealed that vinyl ester-based pipes exhibited a ductile failure under impact, whereas, in the epoxy-based pipes the failure was rather brittle in nature. Low velocity impact response of filament-wound glass fiber reinforced/vinylester (GFRV) and glass fiber reinforced/epoxy (GFRE) pipes were using instrumented drop weight testing machine. From the impact response data and damage evaluation the authors observed that load-time, energy-time, and load-deflection histories were indicative of the damage initiation and damage propagation. Two distinct responses to impact were identified. The first response was elastic deformation during which no gross damage took place. The second response was the initiation and propagation of major damage under elastic and plastic deformation. Energy up to the peak load dissipated in elastic deformation followed by energy dissipation in major damage initiation and propagation. For GFV pipes, the peak load increased with increase in the incident impact energy, while for the GFRE pipes the peak load remained essentially constant and could be considered independent of the magnitude of the incident impact energy. The energy to peak load and the deflection at peak load values for GFRE pipes were found to be substantially lower than the values observed for the GFV pipes. The lower energy to peak load and deflection at peak load values were indicative of the rather brittle nature of the epoxy matrix as compared to the relatively less brittle vinyl ester matrix.

Experimental investigation of mechanical characterization and drilling of fabricated GFRP composites reinforced with Al₂O₃ micro particles were carried out by Rabindra Kumar et al. in [16]. In this paper, the authors studied fabrication of glass fiber composites with microparticles in order to ameliorate the mechanical attributes such as tensile, flexural, impact strength and hardness by conducting tests such as tensile strength test, flexural strength, impact and micro Vickers hardness test, respectively. In order to assemble the structural parts made by composites with the help of rivets and joints or nut-bolts, it is obligatory to drill the composites to make a hole. During the exit and the entry of the drill bit in the hole, composites undergo severe damage in the topmost layer and bottom-most layer which in turn results in the delamination of the layers. So in this work, the drilling process parameters such as cçognate speed, feed and the weight percentage of alumina microparticles were optimized in order to optimize the output parameters like thrust force and delamination factor of the composites. The optimization of the parameters was done according to retaliation surface paradigm concept. The optimum values of input parameters were 1213 rpm speed, 0.16 mm/rev feed and 5.2 % wt. % of alumina microparticles. The corresponding optimal parameters for these parameters were 179.4 N thrust force, entry delamination factor 1.12 and exit delamination factor 1.17 with the desirability of 0.838.

Ijaz et al. studied fatigue delamination crack growth in GFRP composite laminates in [17]. GFRP composite materials are prone to the initiation and propagation of delamination crack growth between different plies forming the laminate. The crack propagation may ultimately result in the failure of GFRP laminates as structural parts. In this work, a comprehensive mathematical model is presented to study the delamination crack growth in GFRP composite laminates under fatigue loading. A classical static damage model proposed by Allix and Ladeveze is modified as a fatigue damage model. Subsequently, the model is implemented in commercial finite element software via UMAT subroutine. The results obtained by the finite element simulations verify the experimental findings of Kenane and Benzeggagh for the fatigue crack growth in GFRP composite laminates. In this study, delamination crack growth simulations for the GFRP composite laminates under the fatigue loading...
are presented. Details of the proposed mathematical model are also explained. The model is implemented in CAST3M software via UMAT subroutine. The crack growth rates obtained from FE analysis are plotted against the energy release rates to obtain the linear Paris plot behavior for mode I and mode II load cases. The simulation results are compared with the available experimental data of GFRP composite laminate and were found to be in good approximation. FE analysis results predicted the large crack growth rates at high amplitude for the applied loading values.

III. CONCLUSION

The literature review provided in the previous section highlights the properties and manufacturing methods of GFRP composite laminates. The methodologies suggested by the authors give an insight into the advancements made in the area of composites. It can be observed that GFRP composite laminates can be successfully fabricated by different techniques like hand layup method with varies compositions of matrix and reinforcement. GFRP composite laminates can also be fabricated by twin rolling method that can lead to exhibit improved mechanical properties.

Acknowledgement

The authors are thankful to the Management, R & D centre, Department of Mechanical Engineering and staff of the Department of Mechanical Engineering, Dr. Ambedkar Institute of Technology for their support and encouragement.

IV. REFERENCES