Interlaminar Stresses in Hemp Reinforced Composites

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Abstract

The purpose of this research is to develop innovative techniques and combinations of constituents to use composites in agricultural, infrastructural and other relevant industries. Industrial, infrastructural, and biodegradable structural applications using hemp fibers are of interest to enhancing environmental sustainability. The products including graphite or hemp reinforced polymers with different volume fractions and orientations are considered. While a large number of products could be used in the commercial production, we explore only two laminates in this investigation. In this paper we are analyzing interlaminar stress components contributing to delamination of composite laminate. Using analytical techniques, effective response characteristics and interlaminar stresses of representative composites are predicted and given in this paper. Based upon this research a set of influencing factors will be identified, specific number of composite laminates will be chosen, manufactured, analyzed and tested for their performance characteristics. This is a step towards further research in progress for comparative studies between predicted and experimental values. We have used hemp fiber properties from reference [2]. For hemp fiber the Young's modulus varies from 2.9 msi to 5.8 msi and Poisson ratio is 0.15. The matrix material properties of EPON 828 with Young's modulus 0.42 msi and Poisson ratio 0.35 are used from reference [1]. For computation of effective properties of $(0/90)_s$ hemp reinforced composite laminates, we have used Young's modulus values 2.9 msi and 5.8 msi separately. Dr. Pagano [3] was the first to recognize the importance of interlaminar phenomena in high-performance composite materials. His discovery of the "stacking sequence phenomenon" led to new practices to reduce the potential for delamination.

Keywords –
hemp, composites, micromechanics, macromechanics, response characteristics.

1. Introduction

Composites have several advantages over conventional infrastructure and aircraft production materials, including reduced weight, reduced number of fasteners, corrosion resistance, and an extended product life. In addition, composites can be designed specifically for certain industrial applications to achieve desired stiffness and strength characteristics. Composites are used on virtually all Department of Defense (DoD) weapon systems, civil engineering and medical applications. Composite structures are proven to reduce weight, fatigue, and corrosion damage, resulting in improved range, payload capability, speed/maneuverability, and stealth. The ability to custom design structural sections, key in the context of this research, reduces touch labor hours related to component production and development. The main disadvantage and largest criticism of using composite materials is the raw materials cost. The current life cycle cost models not taking into account various aspects of estimated cost-ratios is one of the most important challenges decision makers face in determining whether to continue or start production of a new structural system.

Composite manufacturing techniques and this lack of consideration has placed composite materials at a disadvantage compared to metallic materials. Current models treat an increase in raw materials costs as an increase in total life cycle cost. These models do not take into consideration the potential cost savings based on reduced part count and touch labor hours in aircraft production through the use of composites. This lack of consideration leads to an inflated estimated life cycle cost when composites are incorporated into aircraft structures.

This understanding will be utilized in inventing innovative techniques and combinations of constituents; using composites containing agricultural products – namely hemp, *Cannabis sativa* containing <0.3% Δ9-tetrahydrocannabinol which produces strong bast fibers. Hemp fibers have been used for over 10,000 years in textiles and ropes. From the mid-15th to early 19th centuries, hemp was an essential commodity for producing canvas and ropes for military and trading ships. Modern industrial applications for hemp fiber include hempcrete insulations and composites. This work evaluates hemp as a method for reinforcing laminates for DoD, industrial, and agricultural applications.

1.1 Objectives

This work leads to the development of micro and macro level analysis method for investigating response characteristics of hemp reinforced composite laminates. The properties available in literature [2] are used in an Automated System for Composite Analysis (ASCA) [1] to analyze hemp reinforced composites. In order to show the significance of interlaminar stresses in free edge regions leading to delamination, a set of relevant hemp reinforced laminates are considered and analyzed. This work provides a foundation for experimental work to develop appropriate micro/macro model input parameters and comparisons for composite response characteristics.

2. Literature Review

ASCA [1] provides analysis techniques for micro and macro mechanical response of composites widely used in aircraft, spacecraft, and auto industry. The pioneering work of Dr. N. J/. Pagano [3] led him to Engineering and Science Hall of Fame. Extensive work [3-8] on hemp fiber reinforced composite is steering the research towards the use of environmentally friendly applications. There is not much mechanics related work done in hemp reinforced composites. As an example, we have selected two cases of hemp fiber reinforced EPON 828 matrix laminates using fiber constituent properties from reference [2]. For hemp fiber the Young’s modulus is 2.9 msi (second case 5,8 msi) and Poisson ratio is 0.15. The matrix material properties of EPON 828 with Young’s modulus 0.42 msi and Poisson ratio 0.35 are used from reference [1].

3. Methods

Broad aspects of mechanical response of composites and their products are given in reference [1]. We started with a micromechanics model using 3-dimensional model called NDSANDS (N-Directional Stiffness AND Strength). Figure 1 shows the flow of sequence of calculations.

Micro-Macro System for Laminate Analysis

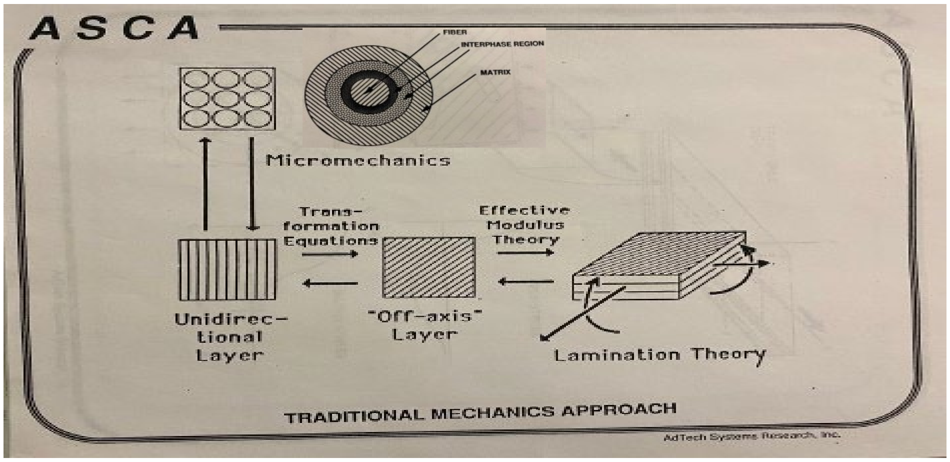

Figure 1. micro and macro modeling for composites.

Using constituent properties of fiber and matrix with volume fraction of the constituents, we calculate the ply stiffness properties. Further, using the ply properties, ply orientations, and thickness, we calculated the effective laminate properties based upon a composite Laminate Analysis (CLAP) module of ASCA, Table 1. In addition, we computed interlaminar stresses for Hemp/EPON $(0/90)_s$ laminate. This shows the important aspect of interlaminar stress variability causing free edge effects.

Table 1: ASCA Modules using Closed Form Solutions

ASCA Modules

1. **Micromechanics - NDSANDS Module**
2. **Lamination Theory - CLAP Module**
3. **Extended Reissner's Variational Principle (free edge stress analysis) FESAP Module**
4. **Extended Reissner's Variational Principle (Stresses in the vicinity of transverse crack) - ALTRAC Module**
5. **Interactive Module**

All These models are based upon linear theory of elasticity.

4. Data Collection

We have used hemp fiber properties from reference [2]. For hemp fiber the Young's modulus varies from 2.9 msi to 5.8 msi and Poisson ratio is 0.15. The matrix material properties of EPON 828 with Young's modulus 0.42 msi and Poisson ratio 0.35 are used from reference [1]. For computation of effective properties, we have used Young's modulus values 2.9 msi and 5.8 msi separately.

5. Results and Discussion

This research evaluates hemp reinforced composite laminates using different ratios of fibers and matrix. There are a number of parameters considered for product development, such as, natural fibers, matrix batch quantities and relevant processing parameters. After making the laminates stress and strength characteristics will be measured, calculated, and compared. Part one of this research is to determine how changing constituent parameters affect laminate material properties. As shown in section 4, micromechanics model [1], provides lamina properties from fiber and matrix constituents' properties. Macromechanics model [1], CLAP module provides the effective laminate properties. The material properties that are estimated are Young's modulus, Poisson's ratio and Shear modulus. Variation of material density along thickness will also be of interest.

5.1 Results for Hemp fiber and EPON 828 matrix laminates

Using the abovementioned input properties for both Hemp/EPON 828 laminates, with E_A=2.9 msi and E_A=5.8 msi, we calculated ply properties using NDSANDS. Using ply properties in CLAP module, effective laminate properties for a fiber volume fraction of 0.55, were computed for $(0/90)_s$ laminate (figure 2) and provided in Tables 2 and 3.

Table 2. Properties of a ply and of the $(0/90)_s$ laminate.

Hemp (E_A =2.9 msi) /EPON 828, V_f=0.55	$(0/90)_s$
E_{11}=1.78 msi	E_x=1.05 msi
E_{22}=E_{33}=0.3 msi	E_y=1.05 msi
ν_{12}=ν_{13}=0.26	ν_{xy}=0.075
ν_{23}=0.3	G_{xy}=0.366 msi
G_{12}=G_{13}=0.366 msi,	
G23=0.114 ms	

Table 3. Properties of a ply and of the $(0/90)_s$ laminate.

Hemp-1 (E_A =5.8 msi) /EPON 828,V_f=0.55	$(0/90)_s$
E_{11}=3.38 msi	E_x=1.92 msi
E_{22}=E_{33}=0.434 msi	E_y=1.92 msi
ν_{12}=ν_{13}=0.25	ν_{xy}=0.06
ν_{23}=0.31	G_{xy}=0.433 msi
G_{12}=G_{13}=0.433 msi	
G_{23}=0.166 msi	

The notations used in tables 2 and 3 are conventional material properties, E, ν and G representing Young's modulus, Poisson Ratio and Shear modulus with subscripts representing the corresponding direction. Laminate properties were calculated by using ASCA's Composite Laminate Analysis Program (CLAP) module.

$(0/90)_s$ Laminate Orientation and Stacking Sequence

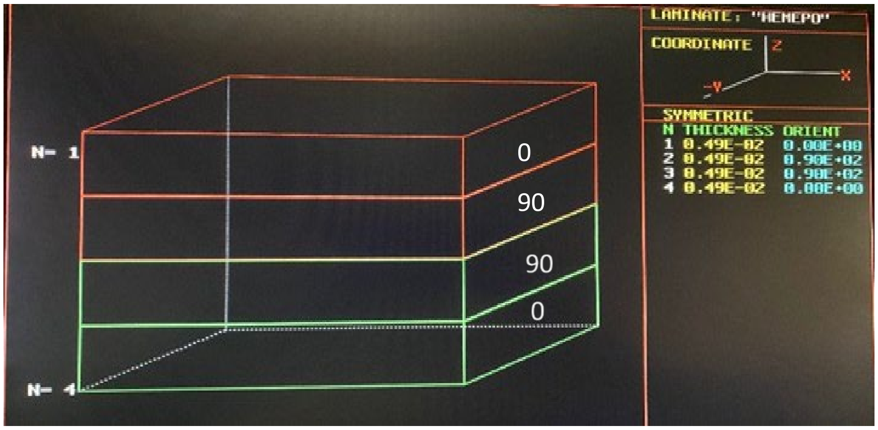

Figure 2. $(0/90)_s$ Laminate Orientation and Stacking Sequence

5.2 Interlaminar Stress Calculations

Using the properties given in table 3, inter-laminar stress components for applied strain in the laminate axis direction of 1.10^{-5} were computed using ASCA. Results for 0 and 90-degree ply interface are given in figure 3. Inter-laminar stress components for the other interface – midsurface is given in figure 4. These results provide an indication as to the variation in the stress components at different locations of the laminate. Using these stress components, appropriate criteria can be applied to predict the failure.

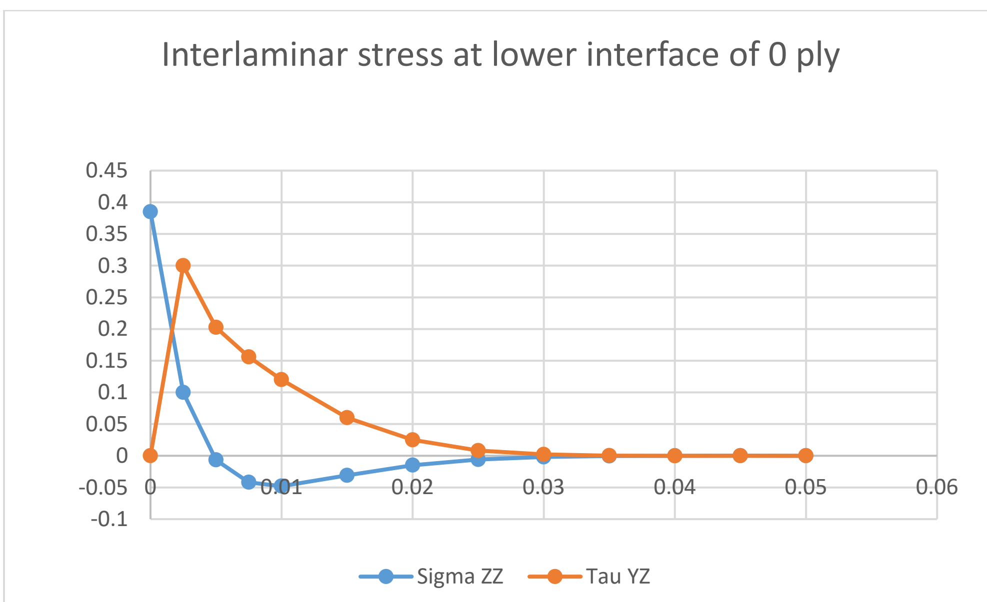

Figure 3. Interlaminar stress components at 0/90 interface of $(0/90)_s$ laminate of HEMP material.

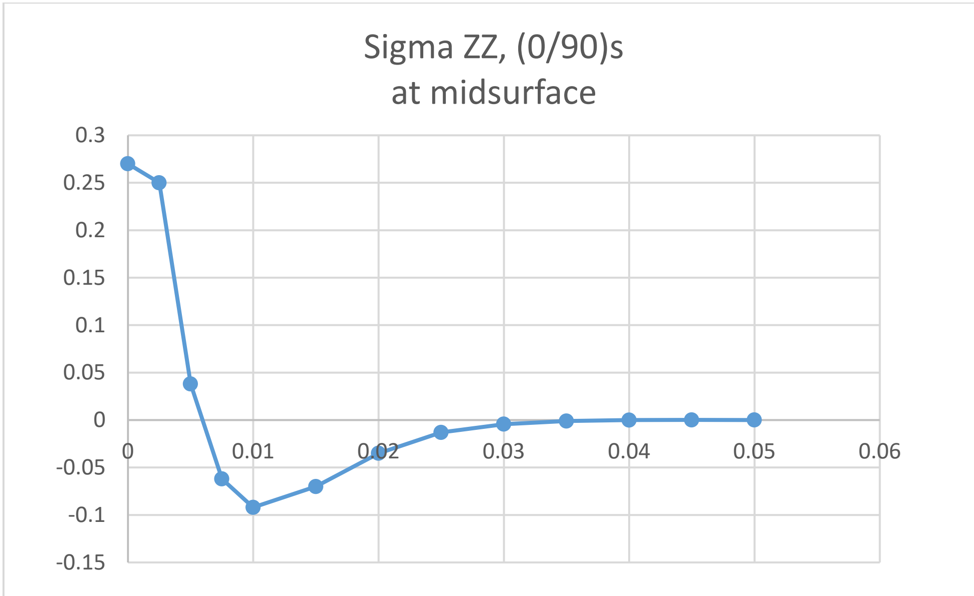

Figure 4. Interlaminar stress components at midsurface of $(0/90)_s$ laminate of HEMP material

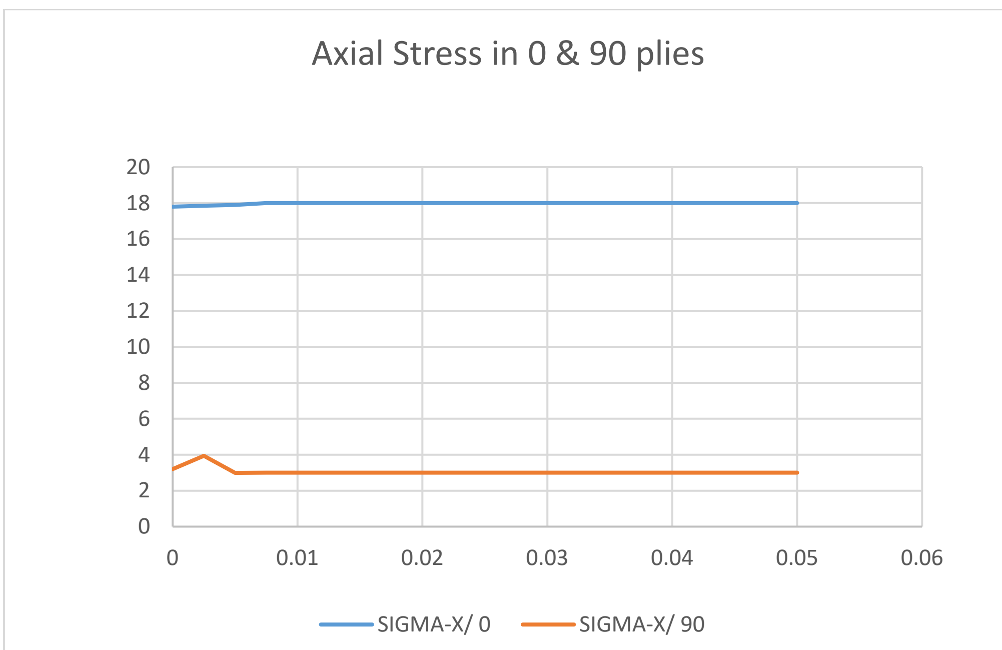

Figure 5. Sigma-x stress component in 0 and 90 degree plies of $(0/90)_s$ laminate of HEMP material

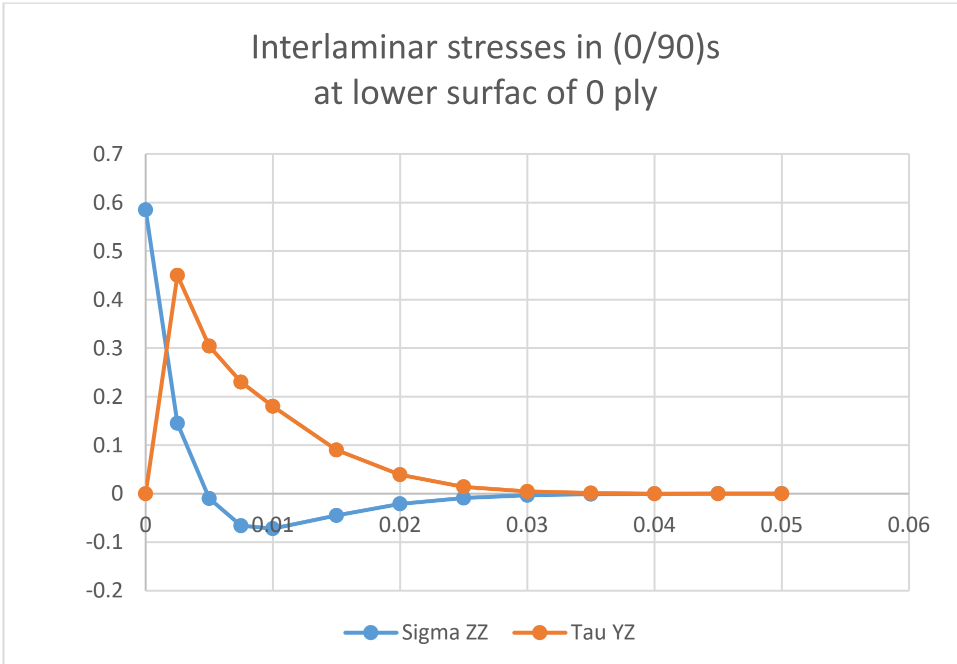

Figure 6. Interlaminar stress components at 0/90 interface of $(0/90)_s$ laminate of HEMP1 material.

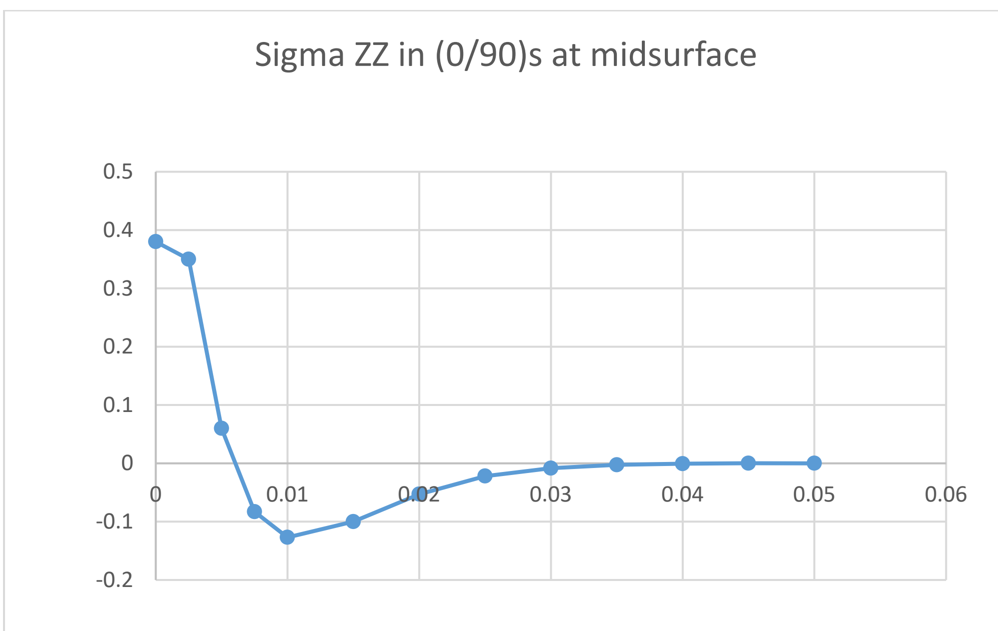

Figure 7. Interlaminar stress components at midsurface of $(0/90)_s$ laminate of HEMP material

5.3 Discussion

Tables 2 and 3 show the variation in effective stiffness properties of the $(0/90)_s$ laminates made with the change of hemp fiber properties 1): E_A=2.9 msi, E_T =0.2 msi, ν_{AT}=ν_{TA}=.15, G_{AT}=1.01 msi; and 2): E_A=5.8 msi, E_T =0.4 msi, ν_{AT}=ν_{TA}=.15, G_{AT}=2.02 msi; A stands for axial and T stands for transverse directions of the fiber; giving an idea as to how to design a composite for required applications.

The variability of directional properties stimulates interlaminar stresses in figures 3 through 7. These results provide an indication as to the variation in the stress components at different locations of the laminate near the free edge. Using these stress components, appropriate criteria can be applied to predict the failure.

5.4 Future Plans

Central State University will be producing hemp fiber to develop our own products. The hemp thus produced will be tested to determine the mechanical properties, such as Young's modulus, Poisson's ratio and tensile strength. A set of composite laminates will be identified, manufactured and tested. The composite analysis code, ASCA, will be used to analyze the laminates. A comparison of experimental and predicted response characteristics will be done to show the efficacy of models used.

6. Conclusion

A foundation is laid for doing mechanics-based research on hemp-fiber-reinforced composites. There has been increasing interest in this field. We have effectively used the mathematical models developed in ASCA for studying the response characteristics of Hemp/EPON 828 and AS4/H3501-6 laminates. Future studies will study and improve the hemp reinforced composites and products.

7. Acknowledgement

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Biography:

Dr. Soni has PhD from University of Roorkee (renamed as IIT Roorkee) India, 1972. Dr. Soni has more than 40 years of experience in teaching and research related to systems engineering design, analytical and experimental mechanics of composite materials and structures. Dr. Soni retired from AFIT in December 2011. Before joining as an Associate Professor in the Air Force Institute of Technology in December 2005, Dr. Soni was involved in AdTech Systems Research Inc as President and CEO for more than 20 years (1984- 2005). He has worked as a senior Scientist for the University of Dayton Research Institute (1981- 1984) conducting research in composite materials and structures. Dr. Soni's recent studies include: a) Cost modeling of composite Aircrafts; b) Systems Engineering Approach to Integrated Health Monitoring System for Aging Aircrafts; and c) Ballistic response of co-cured adhesive bonded composite joints. Dr. Soni is author/ co-author of 100+ research publications in the field of mechanics of solids and structures with special emphasis on composites. Dr. Soni is a Fellow of the American Society for Composites and A Google Scholar. He has won numerous awards including Co-author of Air Force Materials Laboratory's Cleary Award publication, State of Ohio Edison Emerging Technology Award, Enterprise Spirit Award of Kettering Moraine and Oakwood Chamber of Commerce; and Engineering Science Foundation (Affiliate Society Council) Award for Outstanding Professional Achievement for his accomplishments. Dr. Soni is a Heartfulness meditation trainer for more than 30 years.

Dr. Sritharan has PhD Civil Engineering, Colorado State University, Fort Collins, CO; 1984. Dr. Sritharan is a Professor of Water Resources Management, C.J. McLin International Center for Water Resources Management, Central State University, Ohio. He is actively engaged in numerous areas of environmental engineering & water resources management research & education. His areas of research include Surface Hydraulics, Sub-surface Hydraulics, Water Resources Systems Analysis, Hydrology, Water Quality, and Environmental Engineering, and Irrigation and Drainage. He has worked on, a) Water Use and Stream-Aquifer-Phreatophyte Interaction Along a Tamarisk-Dominated Segment of the Lower Colorado River; b) Application of GIS in Evaluating the Potential Impacts of Land Application of Biosolids on Human Health, in Geospatial Technologies in Environmental Management, Geotechnologies and the Environment. Professor Sri has held various leadership positions such as, Dean of College of Science and Engineering and Founding Director of the Land Grant Program at Central State University.

Dr. Schluttenhofer has PhD from the Department of Plant & Soil Sciences, University of Kentucky, Lexington, KY; 2016. Dr. Schluttenhofer is a Research Assistant Professor of Natural Products at Central State University, Ohio. He is leading research and development efforts in hemp production and applications in Ohio. Current research activities focus on understanding production, processing, and new uses for hemp. He has worked on a) the chemistry of hemp cigarettes and vape products; b) using hemp grain as a feed ingredient for fish; c) elucidating impacts of manure application to hemp; and d) evaluating varieties and breeding new hemp cultivars.