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Efficient Computational Analysis of Silicon Dioxide Nano-Composites Utilizing ANSYS for Structural and Functional Optimization

Sarath Raj N. S[1], Dr. Pon Selvan[2], Dr. Amiya Bhaumik[3]

[1,2,3]Lincoln University College, Malaysia

Abstract: The development and use of innovative engineering materials as well as the Finite Element Method (FEM) in structural analysis are examined in this study. It emphasizes the important developments in material science that occurred during World War II, with particular attention on the creation of superalloys, composites, and nanomaterials, and their crucial roles in the nuclear and aerospace industries. The paper highlights the significance of FEM in contemporary engineering by exploring its adaptability and problems in studying complex structures. ANSYS software is used to analyze two distinct material specimens: a control without nanofillers, and one with silicon dioxide nanofillers. The study highlights the need of precise modeling and analysis in engineering designs and highlights the role that FEM plays in forecasting the behavior of composite materials under different circumstances. It also considers the historical background of these materials and techniques, illustrating how they have influenced engineering and technology today.

Keywords: Composite Materials, FEM, Ansys, SiO2, Nanofiller.

1. INTRODUCTION

Historically, human ingenuity has often manifested through groundbreaking discoveries in materials and technologies, with such advancements being integral to overcoming contemporary challenges. A notable period of rapid material innovation occurred during World War II, when the exigencies of war drove metallurgists and engineers to new pinnacles of discovery. The fruits of their labor have since had profound implications across various industries, with aerospace and nuclear sectors being particularly benefitted. The evolution of engineering materials reached a significant milestone during the World War II era, with metallurgists making substantial strides in the development of high-performance materials. These materials, including superalloys, composites, and nanomaterials, have since become quintessential in addressing the intricate demands of modern engineering applications, particularly in aerospace and nuclear industries.

Superalloys, primarily composed of nickel, iron-nickel, and cobalt, have been seminal in jet engine applications due to their exceptional heat resistance and retention of mechanical properties at high temperatures [1]. Their robustness under extreme conditions makes them invaluable in both aerospace and nuclear settings, with some nuclear plants employing nickel-based superalloys for critical components like reactor cores and control rods [2]. On the other hand, composites represent a class of multi-phase materials offering a harmonious blend of high strength, light weight, and corrosion resistance. These attributes have catapulted composites to the forefront of material choices for structural components in aircraft, space vehicles, automobiles, electronic gadgets, medical equipment, and packaging sectors.

Among the pantheon of modern materials, nanomaterials embody the cutting edge, with their unique properties engendering novel solutions to age-old problems. For instance, Carbon Nanotube Metal Matrix Composites (CNT-MMCs) are lauded for their high tensile strength and electrical conductivity, with ongoing research exploring their potential in aerospace applications [3]. More broadly, nanotechnology is ushering a paradigm shift in material science, with nanomaterials beginning to supplant traditional metals in aerospace and other high-tech industries, driven by their superior mechanical and environmental attributes [4]. Today, the palette of commercial engineering materials has burgeoned to encompass over 50,000 varieties, offering engineers a rich tapestry of options to meet the diverse and exacting requirements of modern-day projects.

Structural analysis investigations are indispensable in numerous research endeavors, facilitating the acquisition of vital structural characteristics like stress, deformation, displacement, vibrations, and thermal properties. A suite of commercially available Finite Element Method (FEM) software tools, including ANSYS, NASTRAN, and POINTWISE serve as powerful allies in assessing the mechanical behavior of material structures, thus underpinning the reliable design and optimization of engineering systems. The emergence and progression of these materials and technologies underscore a dynamic interplay between human ingenuity and the exigencies of the time. The journey from the crucible of war to the pinnacles of modern engineering marvels encapsulates a narrative of relentless human endeavor and the indomitable spirit of innovation.

In conclusion, the rich tapestry of engineering materials, evolved through historical exigencies and human ingenuity, continues to fuel the engines of innovation across myriad industries. The seminal role of metallurgists and engineers in advancing the frontiers of material science and technology stands as a testament to the enduring legacy of human creativity and the boundless potential of engineering to shape the future.

2. SILICON DI OXIDE NANOFILLER

Silicon dioxide, commonly known as silica and represented chemically as SiO_2, originates from silicon and has been a crucial component in improving polymer composites, particularly when used in its nanoparticle form [5]. Research focusing on thermoplastic hybrid composites has revealed the significant role nano-silica plays, especially as a nanofiller in aramid multi-axial fabric composites, which are vital in ballistic applications. A notable challenge in integrating nanomaterials into composites is their propensity to clump together. To mitigate this, a specific coupling agent, silica, has been employed in research to prevent the clustering of silica nanoparticles. In the process, nano-silica is coated with silane and then integrated into the matrix for creating hybrid composites. In this context, four samples were produced, each treated with an aminopropyl triethoxysilane (AMEO Silane)/ethanol mix. Notably, half of these samples were enriched with 30% silane-modified silica nanoparticles to reinforce them. The studies demonstrated that using AMEO silane and these modified nanoparticles considerably improved the mechanical properties of the composites [6-8].

Nanofillers, typically solid in nature and distinct in structure from the polymer matrix, are primarily inorganic, with occasional usage of organic materials. These fillers are divided into active and inactive categories, where active fillers elevate the physical and mechanical attributes of the material, and inactive ones aim to increase volume while reducing costs [9]. The incorporation of nanofillers into composite laminates not only reduces their brittleness but also enhances various properties, such as chemical and corrosion resistance, tensile and compressive strengths, flexibility, fracture toughness, shear stress, and even electrical and thermal properties. Vacuum-assisted methods have proven effective in diminishing void-related issues [8]. The diminutive scale of these fillers significantly augments physicochemical interactions and interfaces within the materials, leading to marked enhancements. The altered morphology of nanocomposites, crucial in modifying interfaces, plays a pivotal role in property enhancement. This improvement hinges on the effective blending and surface processing of the materials. The array of possible combinations between the matrix, conventional additives, and nano-fillers results in extensive advancements in various material properties, ranging from fire response to electrical, optical, mechanical, and thermal properties. Moreover, the refinement of filler quality greatly expands the dispersion of these nanocomposites, broadening their application spectrum in diverse fields [10].

3. FINITE ELEMENT METHOD

Throughout engineering and design processes, especially when dealing with intricate structures such as aircraft assemblies, marine infrastructures, and sophisticated mechanical components, precise solutions often remain elusive. To address these intricacies, several approximate methodologies are at the disposal of engineers. These include techniques such as the Galerkin's method, the Finite Difference Method, the Finite Volume Method, and notably, the Finite Element Method (FEM) [11]. Among these, the FEM stands out as an exceptionally versatile tool, providing an avenue to scrutinize structures with complex geometries, diverse materials, and a broad spectrum of boundary conditions and loading scenarios [12].

Diving deeper into the intricacies of Finite Element Analysis (FEA), it can be delineated into three critical stages: Modelling (often termed as the Pre-Processing phase), the core Analysis and Solution stage, followed by the result evaluation, termed the post-processing step [13]. During the preprocessing phase, the nature of the problem is defined in terms of its dimensionality, be it 1D, 2D, or 3D. Subsequent steps involve earmarking suitable material models, selecting elements, meshing strategies, assigning material properties, and instituting correct structural or thermal boundary conditions. Depending on the precise application at hand, various types of loads, including but not limited to thermal, mechanical, electrical, or even magnetic, can be applied [14].

In the contemporary engineering world, several software packages facilitate these processes. For instance, Solid Works is frequently adopted for its prowess in modelling, ensuring precise dimensions and constraints are adhered to [15]. Once a model is constructed, compatibility across platforms becomes essential. Typically, saving in an IGS format guarantees seamless transition to other platforms like ANSYS, a potent tool used for the analysis phase. Within ANSYS, further layers, especially when dealing with composite materials, can be added, and the model prepped with the necessary loads and boundary conditions [16].

The culmination of this rigorous process, the post-processing phase, is indispensable for engineers and designers. It illuminates the response of structures under varied loads - whether they are static, influenced by impact, thermal changes, fatigue, or even torque. This analysis, often prior to the product development phase, provides insights depicted through tables, graphical plots, deflected structural outlines, and even dynamic animations [17]. A quintessential feature in tools like ANSYS is the vivid stress distribution diagrams they produce. This enables engineers to juxtapose experimental data, theoretical predictions, and FEA-derived stress values, ensuring robust and reliable product designs [18].

4. SPECIMEN MATERIALS, TYPES AND METHODOLOGY.

In this experiment, three specimens of materials shall be used. First specimen will be a control specimen with no nanofiller dispersed within the matrix of the material. Second specimen will be dispersed with silicon di oxide nanofillers in the matrix. The third and last specimen will have graphite nanofiller dispersed in the matrix. The geometries of the models that is used in this experiment are pre modeled on other CAD softwares. The geometries that are used are in line with the ASTM standards for different mechanical tests performed on the software. For instance, the model made for tensile strength experiment is in accordance with ASTM D 638M. similarly, compression test model, impact test model, flexural test models and hardness test models are drafted in accordance with ASTM D 1621, ASTM D 256 (Izod/Charpy), ASTM D 790 and ASTM E18-22 (Rockwell's/Brinnel's) respectively.

The ANSYS software was employed to identify potential failure points during tensile, compression, and bending test simulations. Through finite element analysis, the software segregates the test specimen into numerous discrete elements, simulating the actual impact of stress on each specific element. This cumulative effect provides an overall stress value for the entire specimen [19]. The probe tool can be utilized to ascertain the peak stress or force value on every single element.

Numerous numerical iteration software solutions have been developed over time to refine both linear and non-linear analyses of intricate meshed structures. Typically, a consistent finite difference mesh is applied across the test specimen, yet boundaries need to be established and approximated using a combination of horizontal and vertical lines. Fundamental shapes, like triangles and rectangles, can be employed to understand the real-time stress effects on 2-D test samples within finite element modeling software. Lines of any angle can represent curved boundaries for more accurate approximation outcomes. It's important to note that finite element models don't necessarily offer superior approximations compared to finite difference model software. Instead, each is tailored for specific problems based on the context and ease of use. However, it's evident that finite element modeling software is particularly skilled at handling diverse, intricate geometric configurations.

The process of finite element discretization functions by converting a test issue (typically a sample specimen considered as a continuum) into discrete elements. This essentially transforms a continuous space into a set of finite elements, and the unknown field variable is represented using assumed approximation functions within each element. These approximation functions are often termed as interpolation functions in the realm of numerical and computational analysis [20].

Constructing structures with composite materials brings distinct challenges, primarily due to the simultaneous design requirement for both the material and the structure. The paper delves into the analysis of structures constructed from composite materials, often termed as composites. This analysis spans from evaluating the composite material at the micro-level to the broader structures crafted from these materials. ANSYS Mechanical APDL is a widely recognized commercial finite element analysis (FEA) tool. It boasts an intuitive graphical user interface (GUI) complemented by a comprehensive help mechanism. Upon initiation, users can easily traverse through its menus and features. Interestingly, every mouse action within the GUI translates into ANSYS command lines, which are documented in a .log file, making it straightforward for users to understand the functionalities of different commands.

Ansys provides structural analysis software tools that empower engineers from diverse backgrounds and experience levels to address intricate structural engineering challenges with increased speed and efficiency. Using our comprehensive toolset, engineers can conduct finite element analyses (FEA), tailor and automate responses to structural mechanics dilemmas, and evaluate various design scenarios. Employing our software early in the design phase allows businesses to cut costs, streamline design cycles, and expedite product launches.

Regarding the software's analysis process, the subsequent steps were adhered to:

Step 1: Initiate ACP (pre) and input materials like epoxy-saturated E-glass.

Step 2: Specify the requisite number of layers and designate the thickness for each.

Step 3: Establish a static structure and integrate the freshly defined material.

Step 4: Execute the material within the static framework at any desired point and ascertain the point of noticeable failure using a true scale (modifying the exerted force as needed).

Step 5: Incorporate a parameter with incremental adjustments until the force at which the material succumbs is pinpointed.

From the software's diagnostic outcomes, it was discerned that the sample would likely succumb under compression, 3pt bending, and tensile at roughly 200 KN, 20 KN, and 20 KN, respectively.

Taking into account an anticipated increase of 1KN to 10KN for the secondary specimen, Ansys's data indicates that when subject to mechanical testing, it's reasonable to project that the second specimen will outperform the initial one.

Additionally, thermal tests conducted in Ansys yielded encouraging outcomes, although the thermal capacity augmentation wasn't as pronounced as that observed in mechanical assessments.

The approach employed for this research is rooted in the Finite Element Analysis of Strengthened Composite, in which the fiber and resin are systematically layered, maintaining an alignment ranging from 0 to 90 degrees. Several assumptions underpin this methodology: (1) the composite is treated as a homogenous material, (2) the resin's thickness is approximated at 0.00015mm, (3) imperfections in the composite are disregarded, ensuring it's viewed as flawless, (4) fibers are assumed to be impeccably aligned, and (5) fiber distribution is considered uniform. For the purpose of this analysis, the Composite is anchored along the x-axis. Subsequently, a meticulous meshing procedure is undertaken, resulting in a three-dimensional Finite Element mesh to yield precise simulation results.

5. MECHANICAL TESTING OF THE SPECIMENS USING COMPUTATIONAL (APPROXIMATION) ANALYSIS.

5.1. TENSILE TEST

The examination was conducted to highlight the relationship between the stress and strain exerted on the substance, aiming to delineate its novel material characteristics. Subjected to a load of 78KN, the material, measuring 2032x1.905x1 cm, underwent testing. The following outcomes were observed for the control Composite.

	Normal Stresses	Maximum Principal stresses	Strain Energy
Minimum	-354.92 MPa	$-1.978e^{-13}$ MPa	9.3636 e^{-003} MJ
Maximum	5013.6 MPa	5512.6 MPa	3.0295 MJ
Average	82.963 MPa	279.19 MPa	-
Total	-	-	-

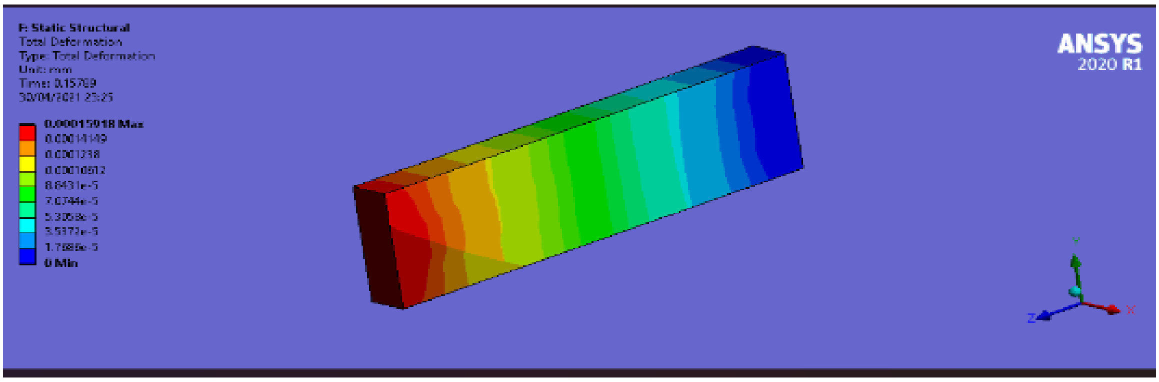

Figure 1: Tension Control Specimen Normal Stress

For Silicon Dioxide the following outcomes were observed:

	Normal Stresses (MPa)	Maximum Principal stresses (MPa)	Strain Energy (MJ)
Minimum	-5.7355e+006	-1.261e-009	8.3227e+006
Maximum	1.8052e+006	3.0276e+006	3.4247e+007
Average	-2.4369e+006	2.2872e+005	-
Total	-	-	-

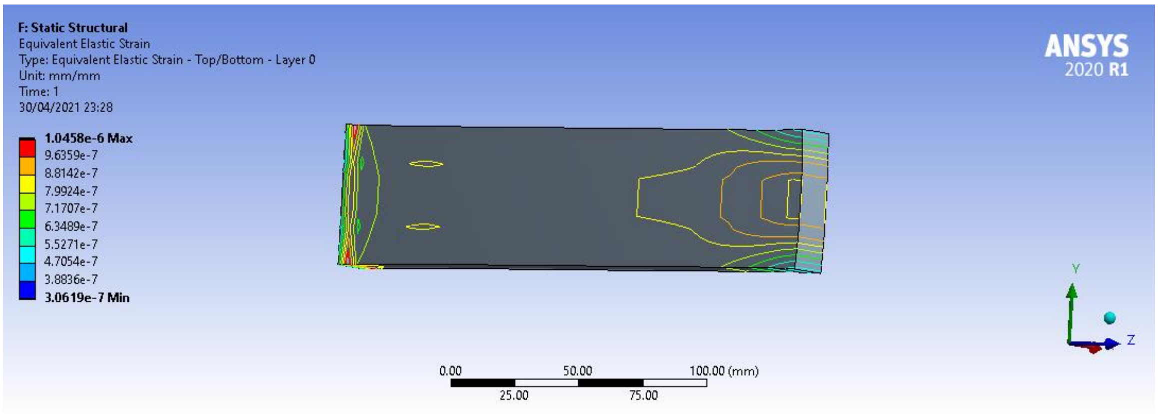

Figure 2: Tension SiO2 Specimen Normal Stress

5.2. COMPRESSION TEST

Compression tests were conducted to determine the peak compressive strength of high silica fiberglass upon the addition of nanofillers. The sample was crafted in compliance with ASTM standards and was evaluated using a universal testing apparatus. A compressive force of 78KN was first applied to the control sample and subsequently to the SiO2 sample. In Ansys, the specimen's dimensions were configured to 30mmx30mmx30mm. A force was exerted at the central point of the specimen, while the base remained stationary. The results of the simulated tensile strength are presented below.

S.NO	Sample	ULTIMATE Tensile Load	Ultimate Tensile Strength
1	Control Sample	78KN	10.618 MPa
2	SiO_2 Sample	78KN	1.9126e+006 MPa

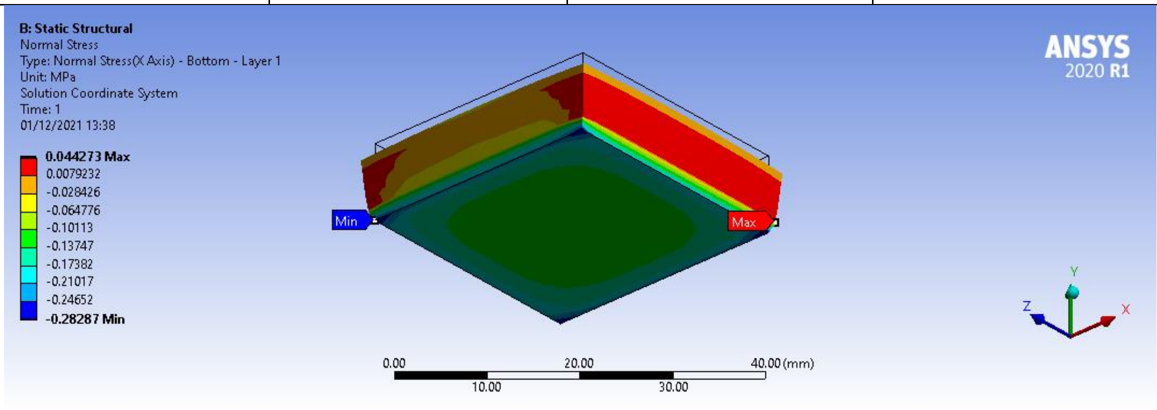

Figure 3: Control Composite Normal Stress Analysis (Compression)

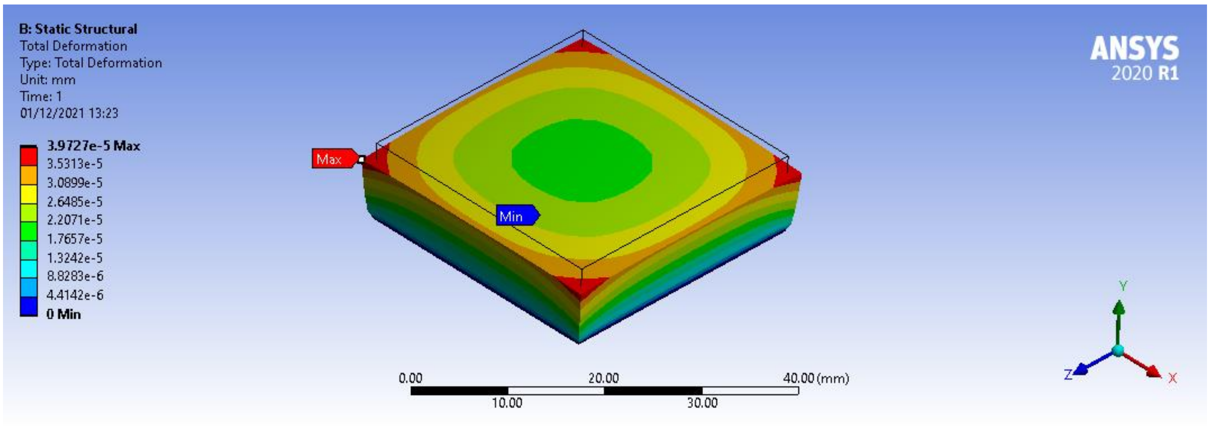

Figure 4: Control Specimen Total Deformation Analysis (Compression)

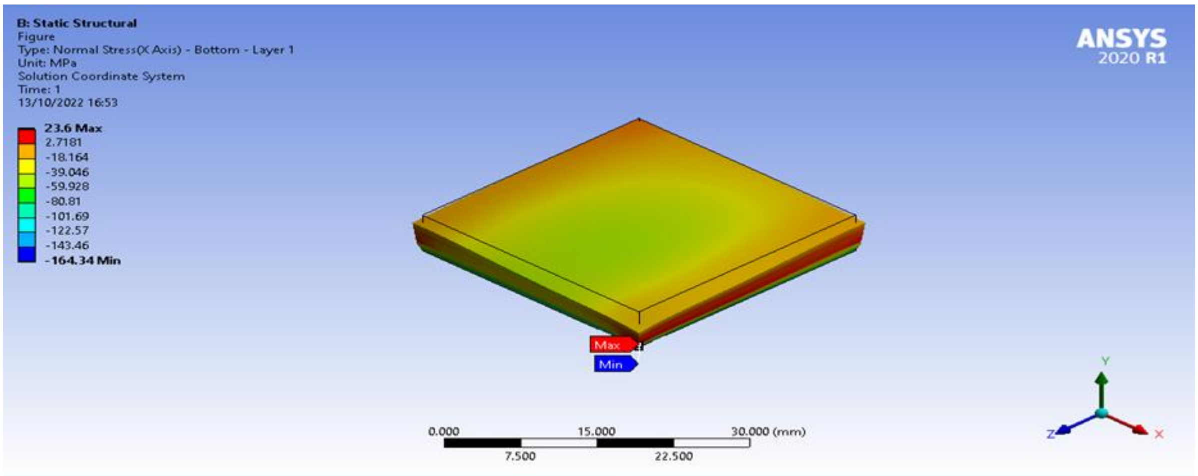

Figure 5: SiO_2 Specimen Normal Stress Analysis(Compression)

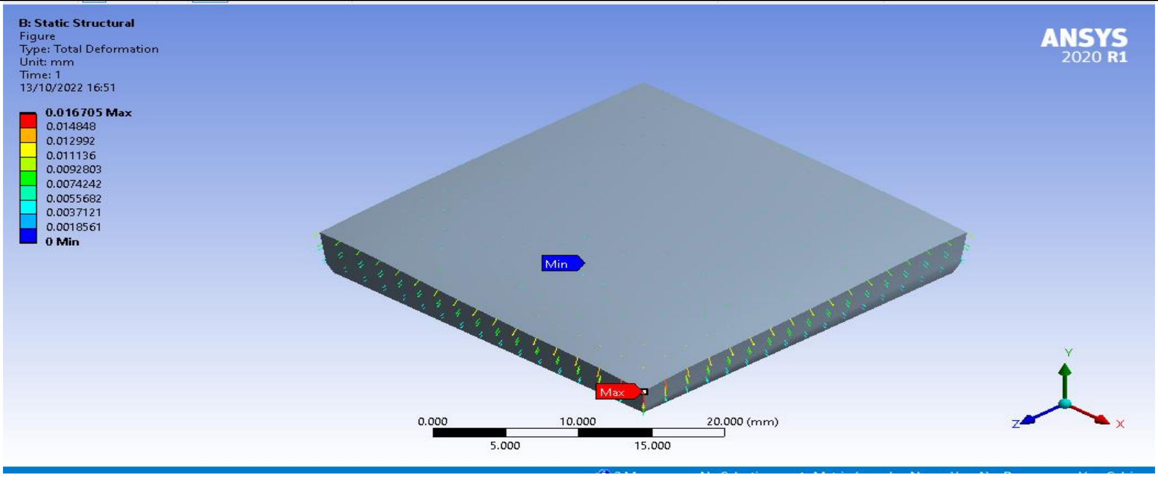

Figure 6: SiO2 Anysis Total deformation (Compression)

5.3. THREE POINT FLEXURAL TEST

The assessment was carried out to identify the diverse stress types resulting in the maximum deformation of the specimen and to evaluate the material's resilience and flexibility. An initial load of 78KN was exerted on the control sample followed by the graphite sample, and the outcomes were juxtaposed. The dimensions of the specimen were configured as 400mmx30mmx30mm, with a 26KN force applied at three distinct points on the sample, while its base remained stationary. Following the simulation, the observed stress and deformation metrics are detailed below.

S.NO	Type of specimen	Type of stresses	Stress Rate	Deformation Rate
1	Control Composite	Normal Stress	326.5MPa	0.98216mm
		Elastic Strain	0.86794mm	
2	SiO_2 Composite	Normal Stress	-2.366e+006 MPa	228.79 mm
		Elastic Strain	0.39969 mm/mm	

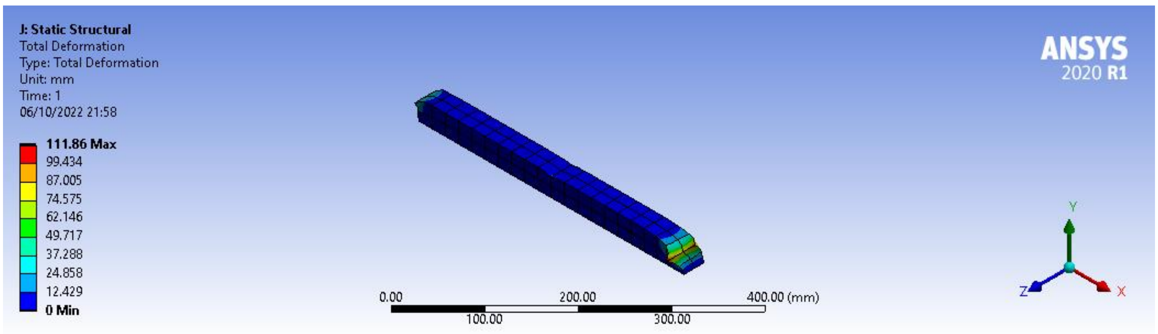

Figure 7: 3-Point Bending Control Specimen Total Deformation

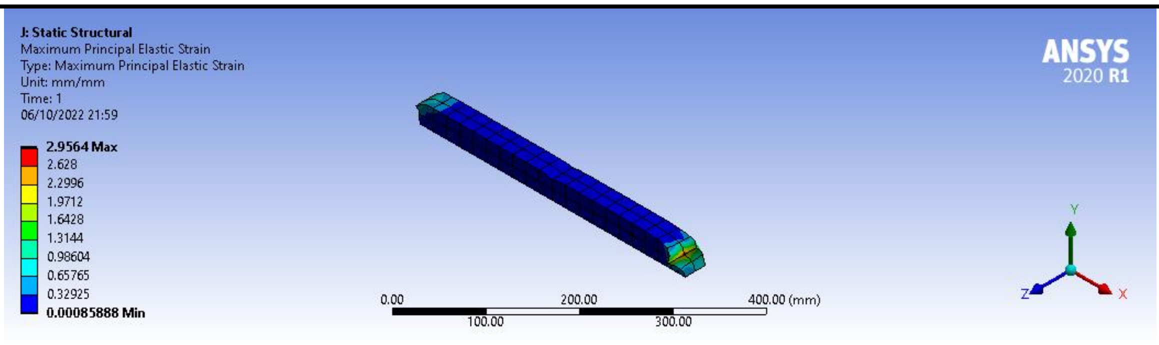

Figure 8: 3-Point Bending Control Specimen Stress Formation

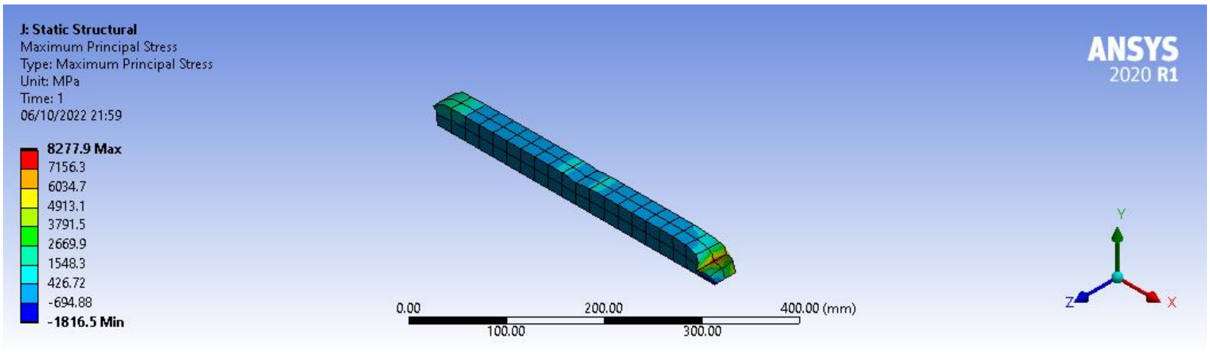

Figure 8: 3-Point Bending Control Specimen Strain Analysis

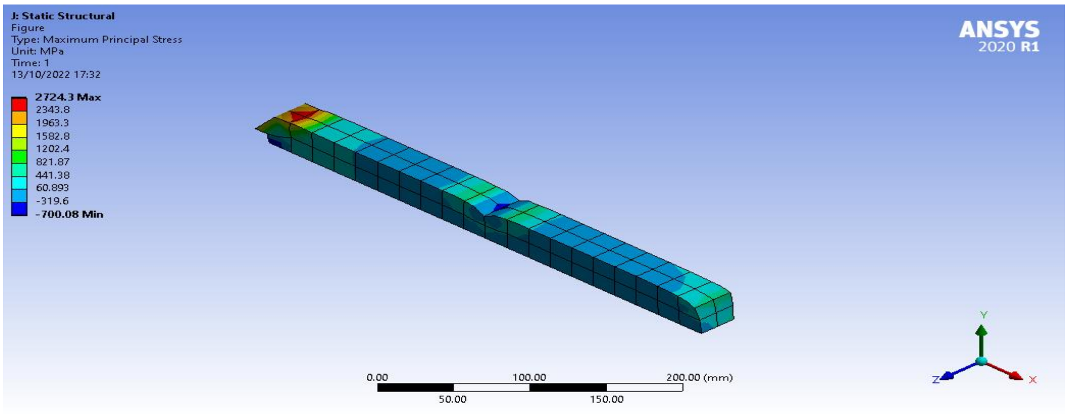

Figure 9: 3-Point Bending SiO_2Specimen Total Deformation

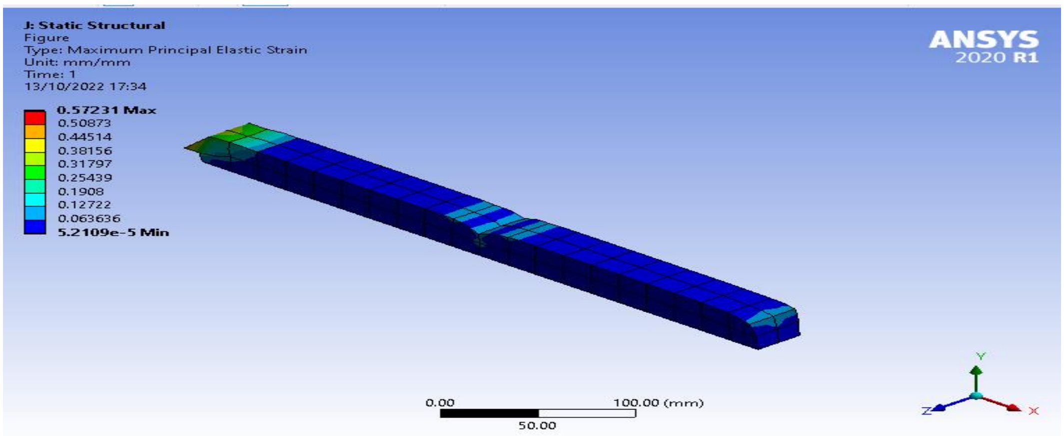

Figure 10: 3-Point Bending SiO_2Specimen Stress Formation

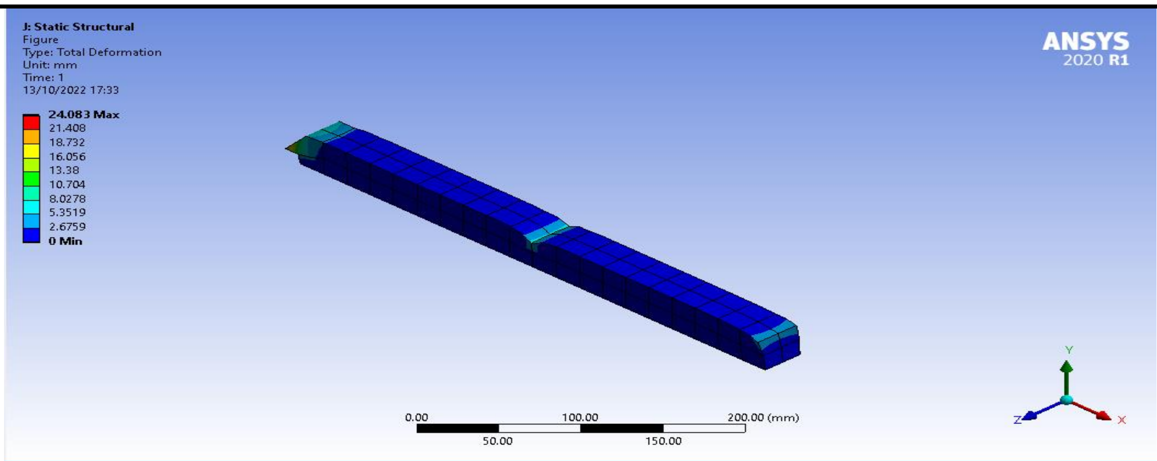

Figure 11: 3-Point Bending SiO_2Specimen Strain Analysis

5.4. IMPACT TEST (IZOD)

The Izod Impact assessment was conducted to evaluate the impact resilience of the samples, which were fabricated in compliance with ASTM Standards. A consistent load of 78KN was directed onto the specimens, illustrating their strength upon the introduction of nano fillers, with the base held stationary. This test provided insight into the material's toughness and highlighted the overall deformation. The findings from the simulation are detailed below.

S.NO	Type of specimen	Impact Strength	Total Deformation
1	Control Composite	84656Mpa	346.9 mm
2	SiO_2 Composite	5.6086e+006 Mpa	156.38 mm

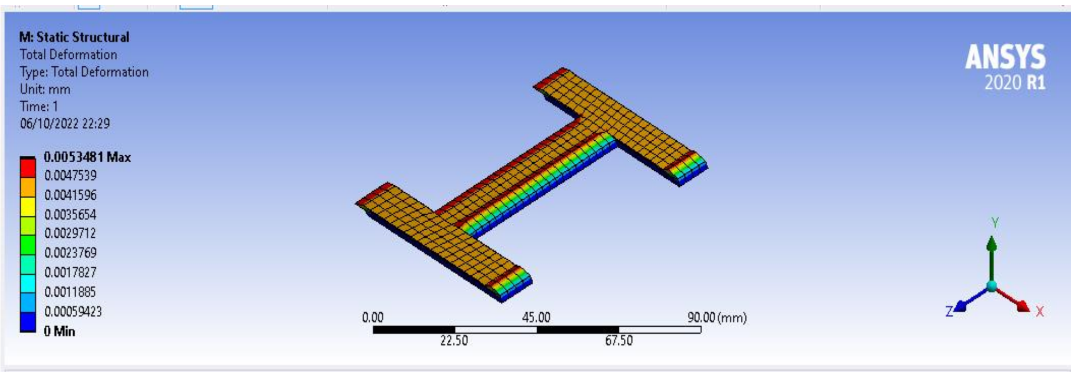

Figure 12: Impact Control Specimen Total Deformation

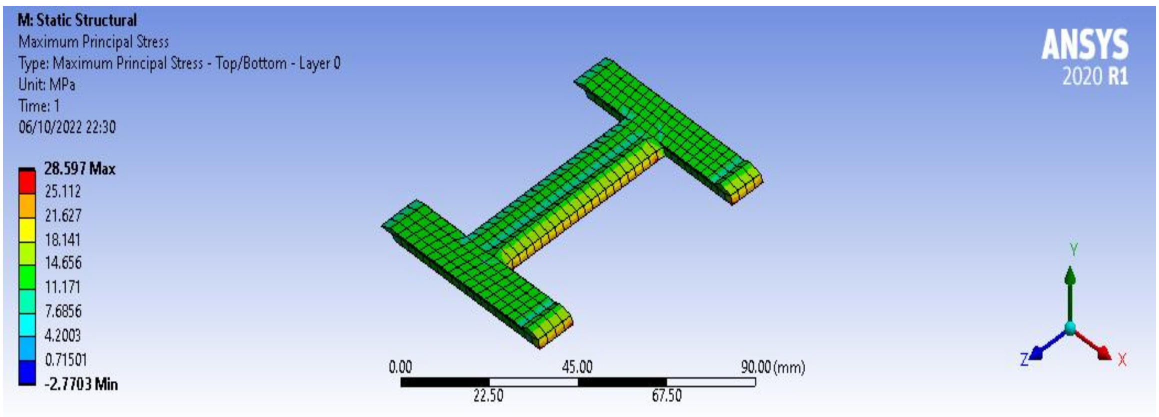

Figure13: Impact Control Specimen Stress Formation

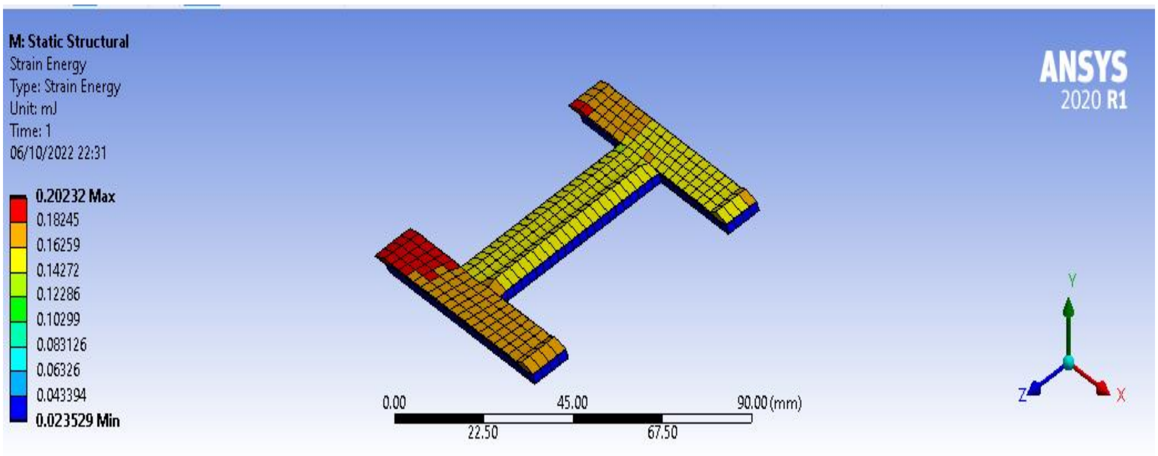

Figure 14: Impact Control Specimen Strain Analysis

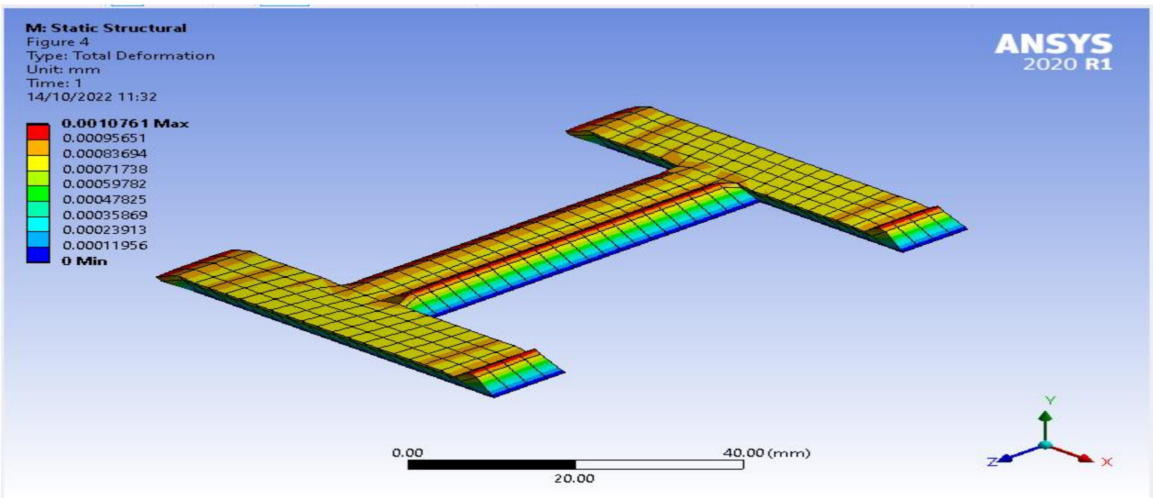

Figure 15: Impact SiO_2Specimen Total Deformation

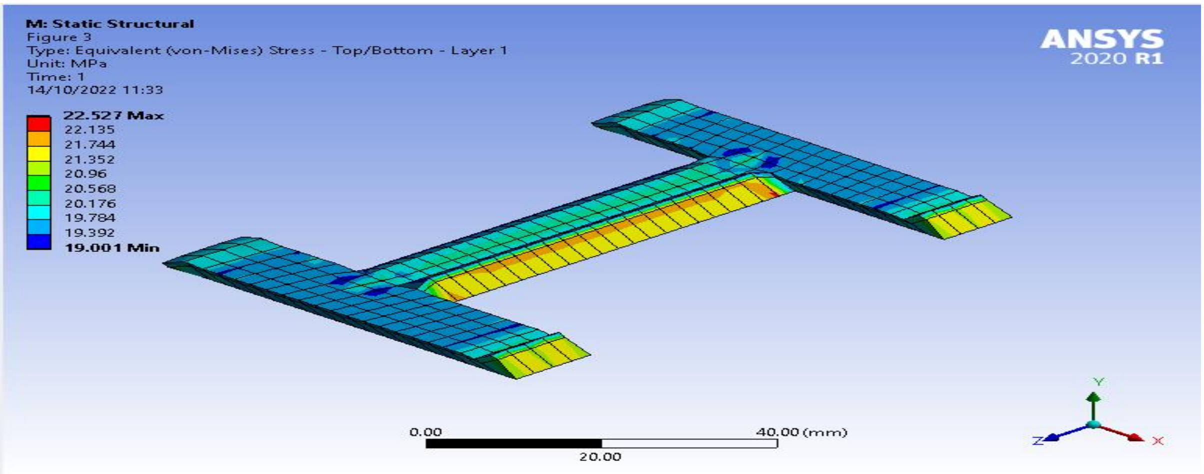

Figure 16: Impact SiO_2Specimen Stress Formation

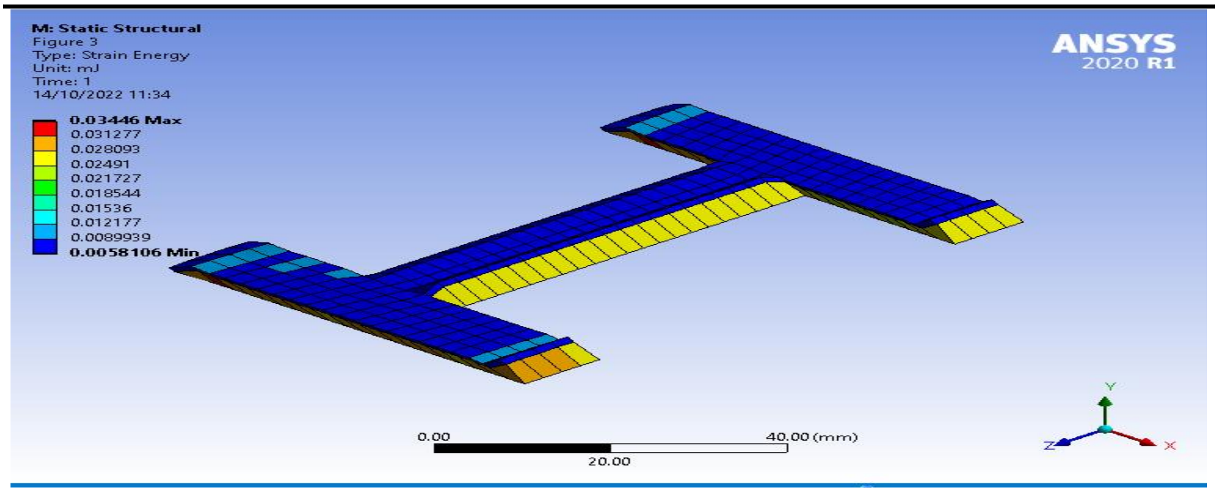

Figure 17: Impact SiO_2Specimen Strain Analysis

5.5. HARDNESS TEST (BRINNEL'S)

The hardness test is carried out to determine the material's ability to resist deformation, revealing the connection between its hardness and other attributes. Given that the material weighs less than 1kg, the Brinell macro hardness test was employed, subjecting the material to a force of 78KN. The following observations were found from the software for SiO2 dispersed Epoxy matrix composite reinforced with high silica fiber galss:

S.No	Type of specimen	Deformation rate	Normal Stress	Strain Energy
1	Control Composite	$4.679x10^{-2}$ mm	-0.32971 MPa	4.3957 MJ
2	SiO_2Composite	251.52 mm	-2.9989 MPa	6.8734MJ

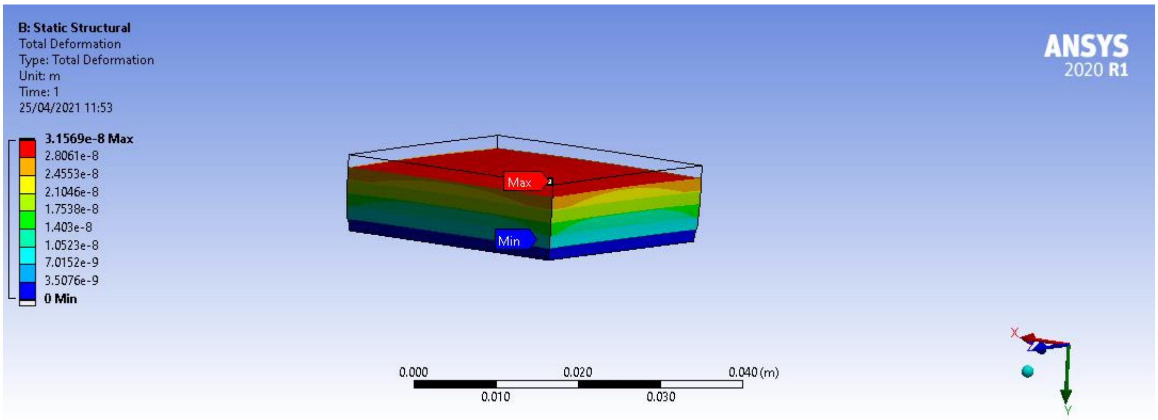

Figure 18: Control Specimen Total Deformation Analysis (Hardness)

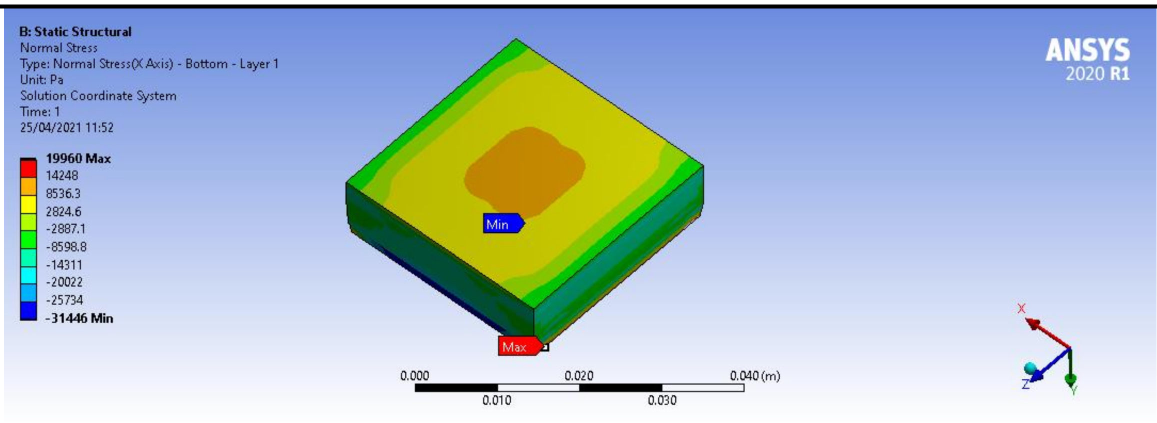

Figure 19: Control Specimen Stress/Strain Analysis (Hardness)

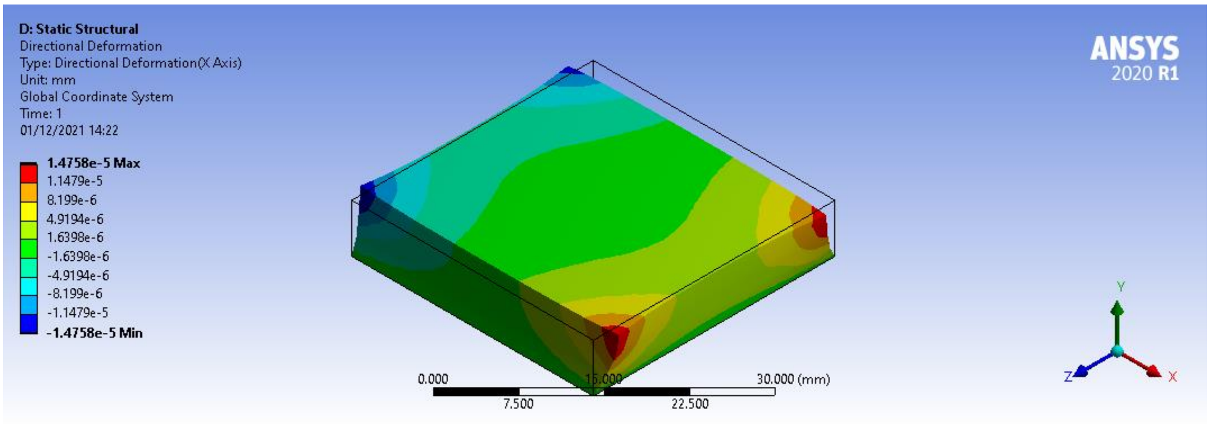

Figure 20: SiO_2Specimen Total Deformation Analsysis (Hardness)

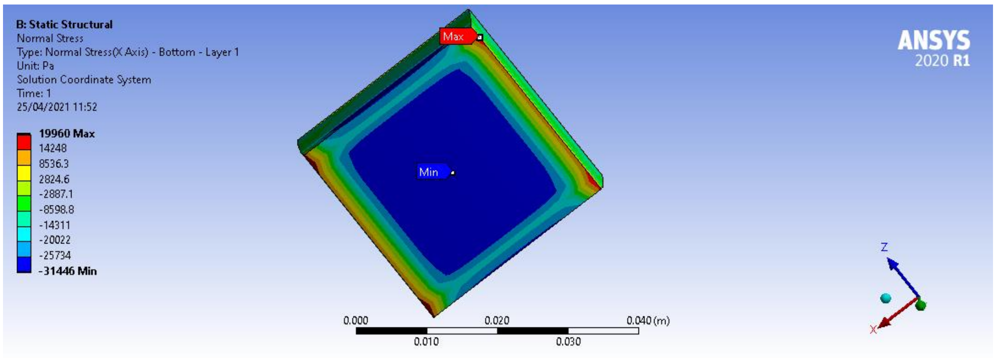

Figure 21: SiO2 Specimen Stress/Strain Analysis (Hardness)

5.6. THERMAL ANALSIS

Thermal Analysis Over Time			
	Temperature	**Raw Specimen**	**Graphite**
Minimum	3176.7 °C	4.3463e-004 W/mm²	.2651e-004 W/mm²
Maximum	3176.7 °C	4.3463e-004 W/mm²	1.6233e-003 W/mm²

The examination was carried out to assess the thermal strength and heat flux of the material. The approach involved maintaining a consistent temperature on all surfaces of the sample while keeping it in a fixed position. Upon conducting the analysis, the following data was obtained for SiO2 dispersed Epoxy matrix composite reinforced with high silica fiber glass:

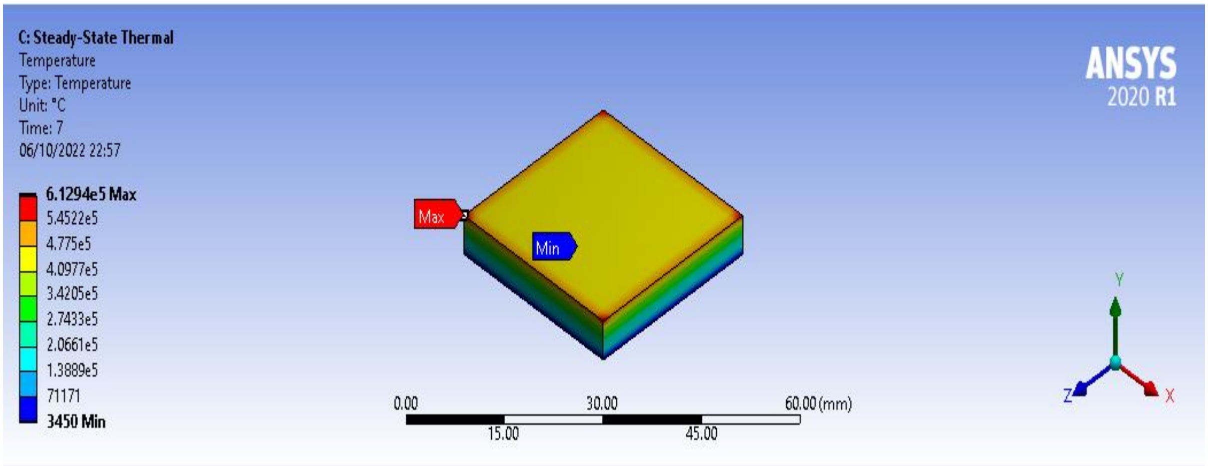

Figure 22: Control Specimen Thermal Analysis

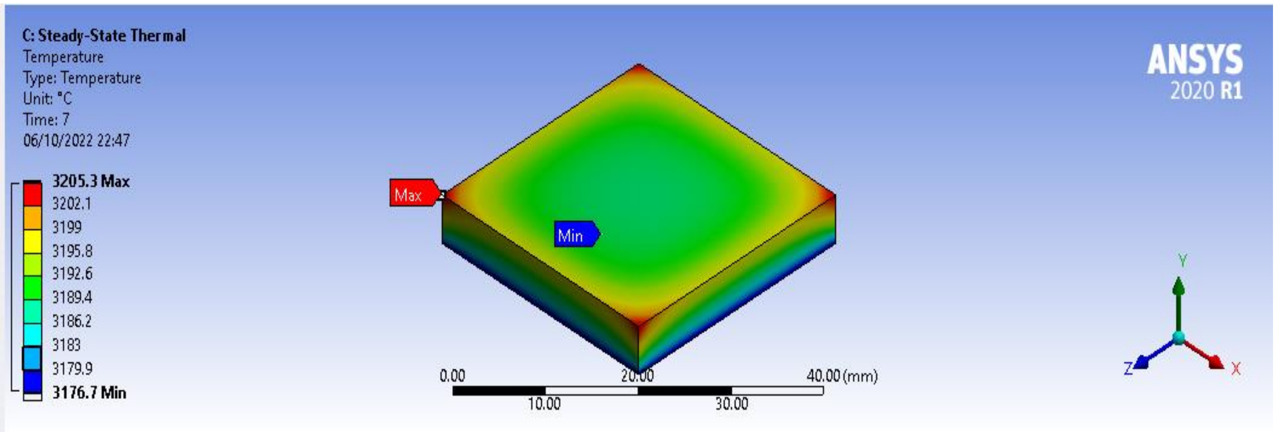

Figure 23: SiO_2Specimen Thermal Analysis

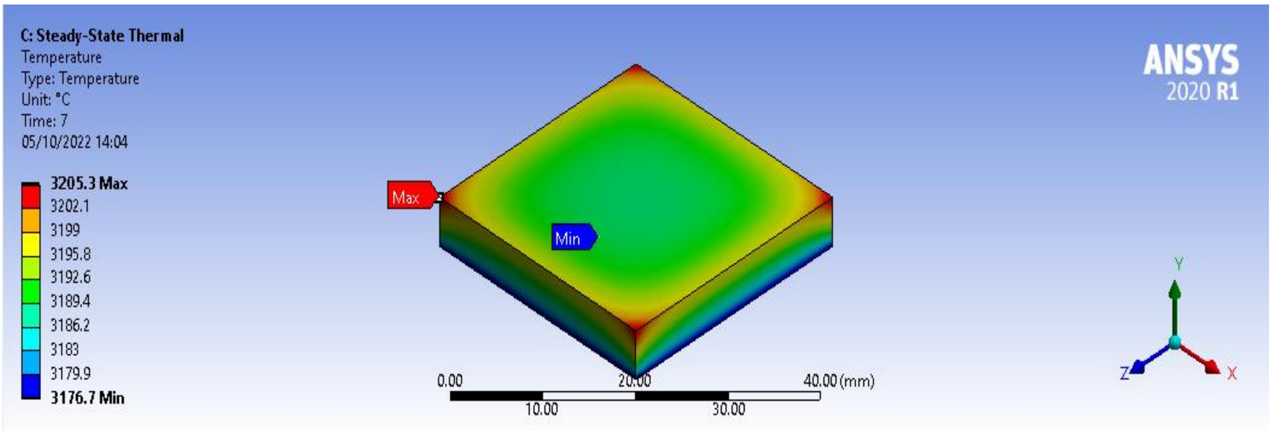

Figure 24: SiO_2Tempreature /Heat Flux Analysis (Compression)

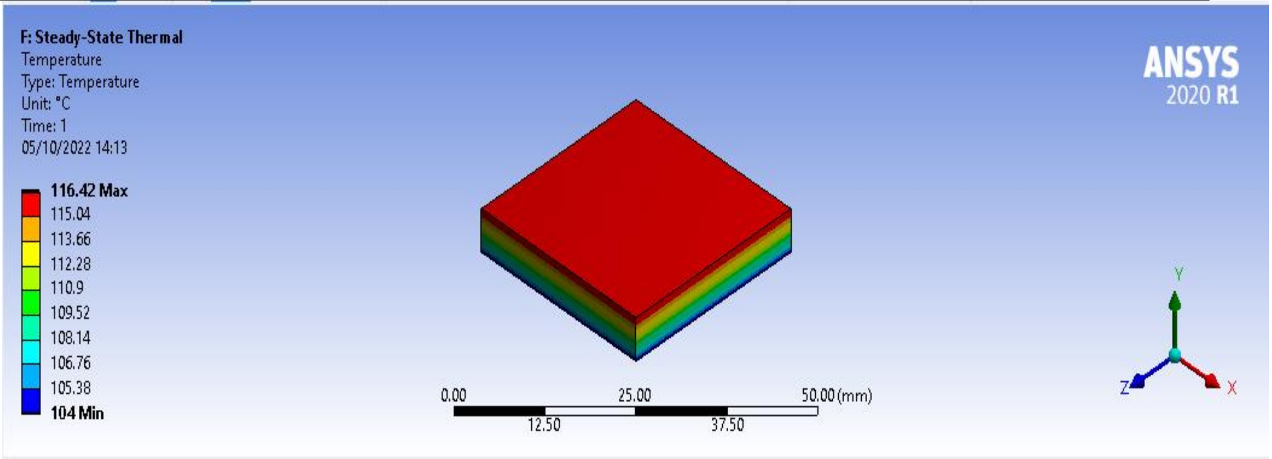

Figure 25: Sio2 specimen Thermal Analysis (Hardness)

6. DISCUSSION ON THE RESULTS

The results obtained can be expressed usingthe increase Vs decrase in strength, stress, strain and enery using the below table.

	Total Deformation	Normal Stress	Ultimate Tensile Strength	Elstic Strain	Energy
Compression	-	-	65% increase	-	-
Hardness	10% decrease	50% decrease	-	12% decrease	-
Tension	-	2% decrease	-	-	Equal amount of energy
Impact	2% decrease	-	8.1% increacse	-	-
3-Point Bending	31% decrease	2.2% decrase	-	51% decrase	-

The table above can be further expalined using the graph below.

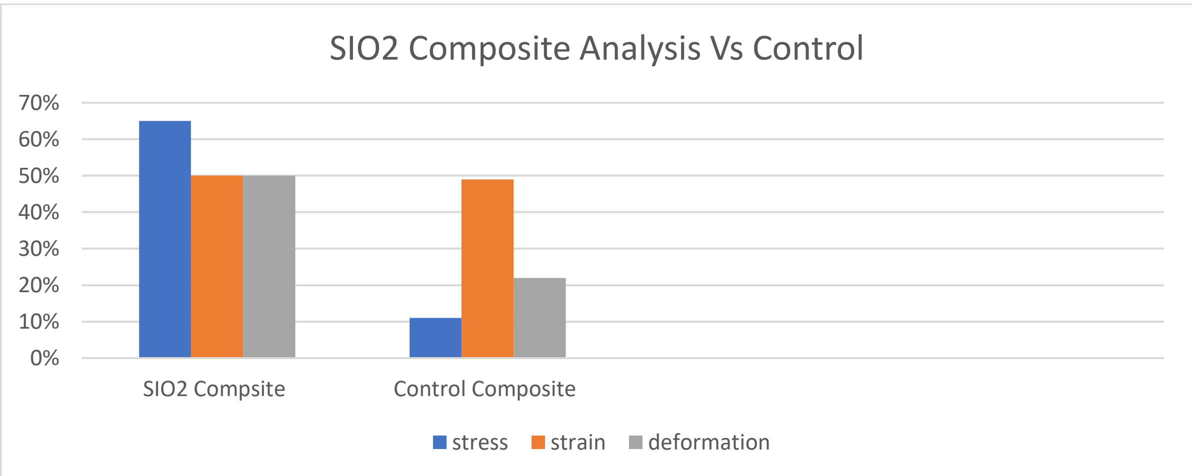

Figure 26: SiO_2 Composite Analysis Vs Control

The analysis sowcased that adding SiO_2 nanofiller to highsilica fiber glass increased its strength and elsaticity rate, and decreased the deformation rate by decreasing the normal stresses and strain acting on the specimen. Adding SiO_2 has increased the material strength by 50% and decreased the normal stresses and strain by 20 to 40%. Furthermore, the thermal analsysis showcased that the SiO_2 specimen had a thermal strength higher than the raw specimen by 20%.

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