

## EFFECT OF GEOMETRIC DISCONTINUITIES ON THERMO-MECHANICAL FRACTURE RESPONSE OF FIBER REINFORCED POLYMER COMPOSITES

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### ABSTRACT

*Fiber reinforced polymer (FRP) composites are increasingly employed in aerospace, automotive, marine, and civil engineering sectors due to their high specific strength, stiffness, and corrosion resistance. This study presents a comprehensive thermo-mechanical fracture analysis of FRP composites with geometric discontinuities, integrating experimental characterization with numerical modeling. However, their structural integrity is significantly challenged by the combined influence of thermal and mechanical loading, particularly in the presence of geometric discontinuities such as holes, notches, and cut-outs that are often unavoidable in practical design. These discontinuities act as stress concentrators, reducing fracture toughness and accelerating crack initiation and propagation. The influence of temperature variations, fiber orientation, and stacking sequence on crack initiation and growth was systematically investigated. Results demonstrate that elevated temperatures lead to matrix softening, fiber-matrix debonding, and reduced interfacial strength, whereas sub-ambient temperatures promote brittle fracture of the polymer phase.*

**Keywords:** *Fiber reinforced polymer (FRP), influence of temperature variations, mechanical loading, geometric discontinuities, fiber-matrix debonding.*

### INTRODUCTION

Commercialization of the composites could be traced to early century when the cellulose fibers were used to reinforce phenolics, urea and melamine resins. Composites in the world of today have wide range of applications, wherever high

strength-to-weight ratio remains and important consideration for use. Its principal use is found in automotive, marine and construction industries. In majority of cases, requiring high performance in the automotive and aerospace industries, the discontinuous phase or filler is in the form of a fiber. In most cases, composite matrices are the thermosets having carbon and ceramics for high temperature applications. Thermosets (epoxy, polysulfones) and thermoplastics (polyetherether ketone, polyimide) due to high strength and performance are pioneer for research and industrial applications. The defects including cracks, holes and inclusions must be considered as essential challenge, due to the major implications they cause on the longevity and structural integrity of engineering components made of composites.

### LITERATURE REVIEW

**Shahram Mahboubzadeh (2024)** Recent advancements in material sciences have underscored the increasing utilization of composite materials, notably polymer-based composites, renowned for their exceptional tensile strength and lightweight characteristics. The tailored fiber structures within these composites, and their strategic placement within the polymer matrix, are

pivotal in modifying the resultant composite's properties. This review article systematically examines the diverse attributes of Fiber-Reinforced Polymer (FRP) composites, including their manufacturing techniques, mechanical properties, and application domains. In this article, the role of natural and artificial fibers in the development of FRP composites is discussed. It has also been observed that new research is being done in the direction of quantum dots (QDs) in order to improve some features of FRP composites. A particular focus is placed on how different fiber weaves and orientations impact the overall performance and utility of FRP components. By aggregating and analyzing current research, this paper aims to elucidate the complexities of FRP composites and forecast trends in their development and use.

**Saswath Ghosh (2024)** Conducting polymer (CP) is an electro active polymer that displays specific electronic properties, including conductivity. The utility of CP-based soft actuators in various biomedical applications has recently been motivated due to their low voltage-driven specialty compared to the widely used high voltage-driven dielectric elastomers. In some biomedical applications, highly delicate CP actuators may be torn or damaged for unknown reasons. In this regard, this study develops a tear fracture model for fiber-reinforced CP actuators to investigate a specific fracture test of mode III, namely, the trousers test, which involves pulling two legs of a cut specimen horizontally apart. The development of the tear fracture model adopts a well-known Griffith criterion along with the thermodynamically consistent continuum mechanics approach. Additionally, prominent strain energy capturing elastomer strain-stiffening at a

moderate strain range is used in conjunction with an empirically established correlation to couple the two internal phenomena, ion diffusion and mechanical deformation of the CP actuators.

**Hui Ruan (2023)** Thermal fracture is prevalent in many engineering problems and is one of the most devastating defects in metal additive manufacturing. Due to the interactive underlying physics involved, the computational simulation of such a process is challenging. In this work, we propose a thermo-mechanical phase-field fracture model, which is based on a thermodynamically consistent derivation. The influence of different coupling terms such as damage-informed thermo mechanics and heat conduction and temperature-dependent fracture properties, as well as different phase-field fracture formulations, are discussed. The model is numerically implemented with the finite element method. Finally, the model is applied to simulate the hot cracking in additive manufacturing. Thereby not only the thermal strain but also the solidification shrinkage is considered. As for the thermal profile, both analytical temperature solution and numerical thermal field around the melting pool are taken into account. Based on the latter approach, the influence of different process parameters is further studied.

**Giada Varra (2023)** The use of classic two-dimensional (2D) shallow water equations (SWE) for flooding simulation in complex urban environments is computationally expensive, due to the need of refined meshes for the representation of obstacles and building. Aiming to reduce the computational burden, a class of sub-grid SWE models, where small-scale building features are preserved on relatively coarse meshes by means of macro scale porosity

parameters, has been recently introduced in the literature. Among the other porosity-based models, the single porosity (SP) model is relevant because the corresponding one-dimensional (1D) Riemann problem is the building block for the construction of many porosity based numerical schemes. Like the Riemann problem connected to mathematical models such as the SWE with variable bed elevation and the 1D Euler equations in contracting pipes, the SP Riemann problem may exhibit multiple solutions for certain initial conditions.

**M. R Zamani (2022)** Composite structures are increasingly being used in various engineering structures such as automotive, aerospace, and civil structures due to their superior properties, namely, high strength-to-weight ratio, impact resistance, and durability. For the purpose of accessibility to other components and possibility of installation, aerospace structures encounter geometrical discontinuities which can lead to a complex structural analysis due to non-isotropic behavior. This paper aims to study the frequency response behavior of a composite lattice conical structure considering the effect of geometric discontinuity stiffened by a circular ring. The lattice structures are made of glass fiber reinforced polymers (GFRP) fabricated using filament winding method and cured in an autoclave.

### **Factors Affecting Thermal Conductivity of Composite Materials**

The knowledge of thermal conductivity of composites is needed for accurate design. Data about thermal conductivity of resin facilitates to reduce stresses related to shrinkage of composites during cure and mismatch in thermal expansion coefficients. Before conducting experiments to determine thermal

conductivity of various composites, knowledge about effect of different parameters influencing thermal conductivity is essential. Fibers Fiber is the reinforcing phase of a composite material. Thermal conductivity of a composite depends upon the thermal conductive nature of the fiber and matrix. Commonly used fibers for composites include Glass, Carbon, and Aramid etc. The microstructure of any fiber plays vital role in carrying heat. The glass fiber has an amorphous structure. It consists of  $\text{SiO}_2$  molecules and forms a three-dimensional silica polyhedral network along the length of the fiber. It behaves nearly isotropic, resulting in nearly same conductivity properties in any direction of the fiber.

### **Micro-Mechanical Representation of DFRC**

In this section, we summarize the 3-D micro-mechanical model, which was developed and validated by for simulating the aligned DFRC. The overview of the micro-mechanical model is illustrated. The model contains an RVE of unidirectional and discontinuous carbon fibers of  $5 \mu\text{m}$  diameter with varying aspect ratios, embedded within a modified thermosetting epoxy matrix (base ink). The fibers, matrix, and fiber/matrix interfaces were explicitly considered. Fibers were randomly distributed along the z axis and uniformly distributed along the direction's transverse to the fibers' axis (x and y). As such, the target fibers' volume fraction of 5.5% and the intermediate fibers' aspect ratios (FARs) of around 50 (i.e., the cases for 3-D printed DFRCs) were achieved. Note that the fibers' distribution in the transverse directions is known to affect the mechanical response of fiber-reinforced composites only under transverse loading, especially when the fiber volume fraction is low.

### **Rate-Dependent Deformation and Failure**

It is identified that the underlying mechanisms of the observed rate-dependent deformation and failure of composites take place among multiple length and time scales. The contributing mechanisms can be roughly classified as: viscosity of composite constituents (polymer, fiber and interfaces); rate-dependency of the fracture mechanism as it is constituted by the different failure processes (e.g., fiber failure with fiber pullout, matrix damage and fiber–matrix interface failure) occurring at microscale level under different loading rates; inertia effects characterized as inertia resistance against rapid deformation, damage formation and crack propagation. Due to material heterogeneity, micro-inertia effects also arise as a result of wave reflection occurring at the interfaces between the constituents, which can result in complex spatiotemporal scenarios of damage and failure evolution, initiated at multiple spots; thermomechanical dissipation as a transition from isothermal to adiabatic deformation and failure process is expected for increasing loading rate; the characteristic fracture time, as there is a threshold time (characteristic fracture time) required to activate cracks.

### **Rate-Dependent Fracture**

A classic example of rate-dependent fracture process zone is the crazing process in glassy polymers. As it was pointed out, craze growth was clearly a time-dependent process. The structure of the craze was revealed as fibrils (main and cross-tie fibrils) separated by the voids. Direct measurements of craze shapes for several glassy polymers, including polystyrene, poly(vinyl chloride) and polycarbonate, had confirmed the similarity to the plastic zone model pointed out that crazing occurs at a

crack tip or in a solid section with a very appreciable increase in volume, which could be correlated to the hydrostatic tensile stress in craze initiation and growth. The theory for crazing growth has been well developed now. Based on the meniscus instability criterion proposed for craze propagation, how resistance to craze propagation increases with entanglement density and was therefore dependent on chain length and molecular characteristics.

### **Mirco-Scale and Meso-Scale Inertia Effects**

Micro-scale and meso-scale inertia effects are both recognized to have contributions to the rate effects, so they should be considered in the numerical model. The heterogeneity of the microstructure of composite materials causes dispersion in wave propagation associated with dynamic loading. This dispersion phenomenon is a result of the local motion of the microstructure-driven by multiple wave reflections occurring at the interfaces between the fiber and polymer matrix. The dispersion and attenuation observed in composites subjected to wave propagation should be reflected in the constitutive model to account for the effect of the microstructure. An “effective stiffness” theory by which the actual composite was transformed into a homogeneous higher-order continuum with a microstructure.

### **Thermo-Mechanical Model**

Temperature effects could be properly considered following the coupled thermo-mechanical framework. Heat generation in bulk material and the fracture process zone should be considered properly with a constitutive model reflecting the influence of temperature. A thermomechanical dissipative cohesive zone model to predict the dynamic crack tip heating increase in brittle amorphous polymers. Developed a

model suitable for the analysis of material interfaces at different scales in which the concept of thermal damage was used to quantify the reduction in the heat flux across the interface.

### Few important facts on Thermo mechanical Treatment

A consistent austenite forms that is far superior to ordinary steels and the hardening forms during controlled cooling process. Carbon ratio in TMT Bars is as low as 0.5% therefore the tensile strength is high and less brittle. The tempering is done at 100°C that increases the strength and ductility. During Thermo mechanical treatment superior ductility enhances in TMT bars therefore, the austenite causes the balance between Strength and Flexibility. The brittle strength increases in TMT Bar relatively. That is why it becomes usable for any type of construction purposes. The Martensite structure consists of consistent RIBS that give superior bonding quality of steel bars in RCC.

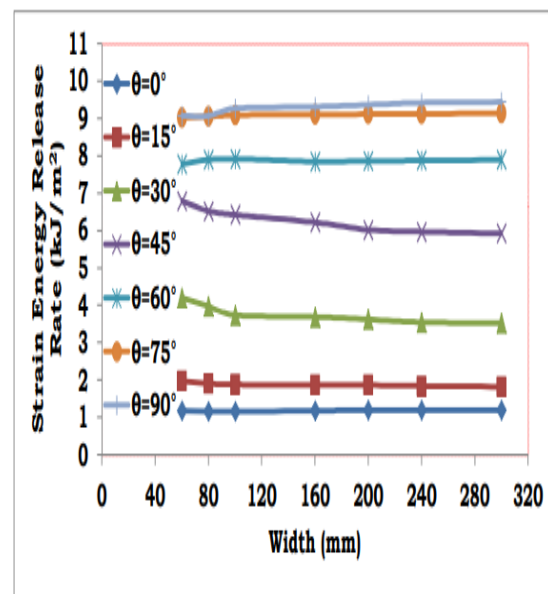
### RESEARCH METHODOLOGY

The composite laminate on SERR is presented by considering the effect of width of laminate, Pressure acting on the laminate, thickness of the laminate, the magnitude of loading effect on the considered laminate and fibre angle effect along with the fibre position. The determined amount of the epoxy resin along with the hardener is thoroughly mixed to eliminate any air entrapped. For the easy removal of the sample, the mould is coated with releasing agent priory. The bottom plate, middle and top plates are used for preparation of the mould. The plates are placed in order and the mixture is poured onto the aligned carbon fibres which are placed uniformly. When a material tends to failure into layers, when load is applied in operating condition, the mode of failure is

known as delamination. Here the laminated material will get separated or deformed into layers of laminas or lamina deformation. Materials like laminates, composites and concrete can fail due to delamination effect while in operation. Even coatings such as surface coatings, paints and films can also delaminate from the substrate that it has been coated too. Delamination is a topic of research interest in Aerospace, Automotive and specialized Industries where composites are being utilized.

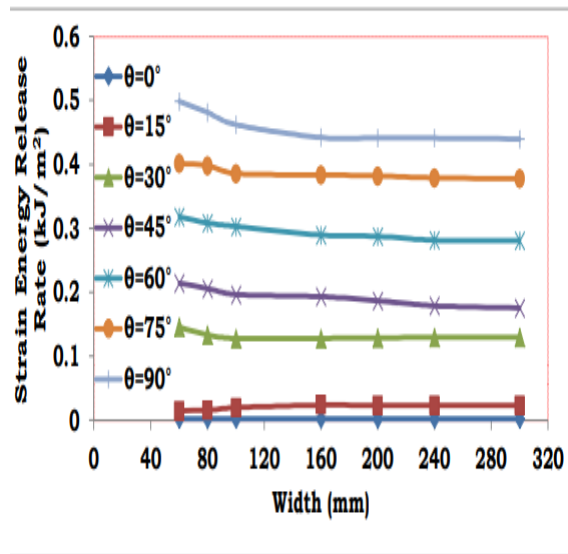
### RESULTS AND DISCUSSIONS

The prime factor for the fracture of any material is to understand the failure mechanism under the influence of various types of loading conditions. If the fracture behaviour is not properly studied of the material structure, this may lead to the failure of the entire structure. So, determination of these single and mixed fracture mode is important to understand the fracture behaviour. The strain energy slightly decreases up to 80mm width of the plate, later there is no significant change in the SERR. The fibre angle position has a significant influence on the SERR.



**Graph 1: Variation in SERR with the increase of width for Mechanical Load of 5 MPa**

With the increase of fibre angle, the SERR is increasing because the amount of SERR depends on the fibre angle. When the fibres are in 0° directions, these fibres offer more resistance to the applied load. As a result, the 0° fibres will offer more resistance to the growth of the crack. The fibres in 90° shows more strain energy than the other fibres considered for the study.



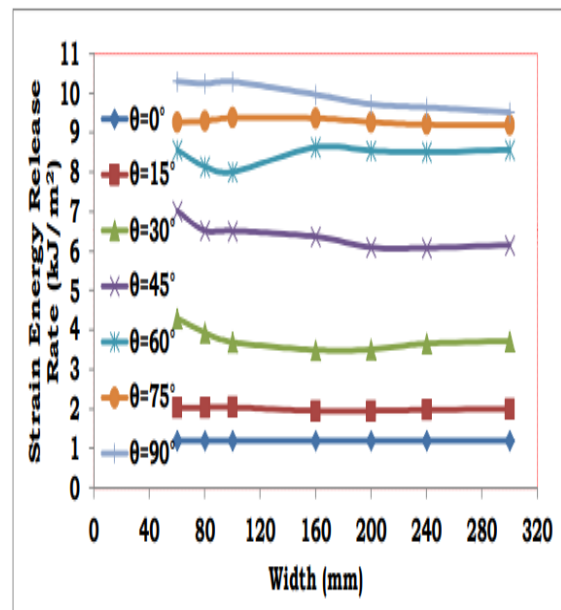
**Graph 2: Deviation in SERR with the increase of width for a Thermal Load of 400°C**

The strain energy slightly decreases up to 100 mm width of the plate, later there is no significant change in the SERR. The fibre angle position has a significant influence on the SERR. With the increase of fibre angle, the SERR is increasing because the amount of SERR depends on the fibre angle. When the fibres are in 0° directions, these fibres offer more resistance to the applied load. Increasing the width of the composite plate has not influencing the SERR after 100mm width.

The effect of width on the SERR for Thermo Mechanical loading for different fibre angles 0°, 15°, 30°, 45°, 60°, 75° and

90°. The loads considered are 4000C and 5 MPa and evaluated the SERR. The SERR is increasing with the increase of fibre angle and noticed a maximum of 90°.

Unlike Thermal loading, the combined loading of Mechanical and Thermal loading has different effect on the strain energy release rate. This type of loading is more expected in real time applications. Under the combined loading the strain energy is slightly falling up to 160 mm width of the plate. Later there is no significant change in the SERR.



**Graph 3: Effect of width in SERR against a Thermo-Mechanical Load of 5 MPa and 400°C**

The response of fibre position under combined loading is not different with pure loading (either Mechanical or Thermal) which means the contribution of matrix in the composite shows the different behaviour under combined loading. The temperature has a significant influence on the matrix strain behaviour

With this result, it is understood that under combined loading of Mechanical and Thermal loading, the selection of matrix is the crucial factor for effective design of composite material.

## CONCLUSIONS

The present investigation into the thermo-mechanical fracture behavior of fiber reinforced polymer (FRP) composites with geometric discontinuities has offered valuable insights into the interplay of material properties, thermal environments, and structural defects on overall integrity. The results establish a fundamental understanding of how fracture resistance, crack initiation, and crack propagation in composites are governed not only by their anisotropic architecture but also by the presence of discontinuities such as notches, holes, cut-outs, and delaminations. The dual influence of thermal and mechanical loading has been shown to critically dictate the fracture performance of FRP composites. Elevated temperature exposure leads to softening of the polymer matrix, reduction in interfacial bonding, and a decline in shear strength. This effect becomes pronounced in composites with discontinuities, where thermal gradients exacerbate stress concentrations. Conversely, at sub-ambient temperatures, the polymer matrix tends to become brittle, inducing premature crack initiation under relatively lower mechanical loads. Thus, temperature-dependent fracture toughness is not a fixed material constant but a function of both environmental and geometric factors. The analysis also highlights that the mismatch in coefficients of thermal expansion (CTE) between fibers and matrix induces localized residual stresses around geometric discontinuities. These stresses significantly influence crack path deviation, delamination, and fiber pull-out. Thermo-mechanical coupling therefore magnifies the complexity of fracture phenomena compared to purely mechanical loading.

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