Localised Fibre Reinforcement for Bearing Regions in 3D Printed Composites

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ABSTRACT
This study investigates the influence of localised continuous fibre toolpaths on the structural behaviour of additive manufactured composite components containing geometric defects. Using a Markforged platform, 40-layer symmetrical specimens ($Onyx_4/GF_{32}/Onyx_4$) were manufactured with a central 6 mm hole. Three distinct configurations were evaluated to assess fibre architecture variations: a baseline quasi-isotropic layout (G1), and two architectures reinforced with 2 (G2) and 4 (G3) concentric circular fibre paths around the hole boundary. Classical Laminate Theory was used to establish the global laminate stiffness, while a geometric reinforcement model quantified local circumferential fibre continuity surrounding the hole, yielding a uniform global in-plane stiffness of 8.76 GPa. Analytical results indicate that while the localised rings result in a negligible global fibre volume variation ($\Delta V_f = 0.10\%$), they significantly enhance geometric fibre path continuity adjacent to the defect (138.23 mm in G3 compared to 0 mm in G1). This localised continuity is hypothesised to optimise stress distribution and load transfer mechanisms under complex bearing stress fields, establishing a predictive analytical framework for subsequent experimental validation.
Keywords: Additive manufacturing; continuous fibre; Onyx; HSHT GF; bearing response; Classical Laminate Theory.

1. INTRODUCTION

The integration of continuous fibre-reinforced polymers into structural applications requires reliable joining techniques; however, mechanical fasteners introduce local stress concentrations that can initiate damage and reduce load-carrying efficiency [1-3]. Conventional composite manufacturing often requires drilling after fabrication, which interrupts continuous reinforcement pathways and reduces the effectiveness of fibre architectures surrounding the fastener region. Continuous fibre additive manufacturing provides an alternative approach by enabling reinforcement placement to be programmed during fabrication, allowing fibres to be steered around geometric features such as holes [3-4]. Despite these advantages, the relationship between local toolpath architecture and bearing behaviour in additively manufactured composites remains insufficiently understood. This study builds on such findings by developing an analytical framework to investigate how localized concentric fibre reinforcement around a fastener hole alters local geometric fibre continuity and material stiffness fields.

1.1 Aims and Objectives

To establish an analytical and geometric baseline evaluating the influence of local continuous fibre architectures around a geometric defect, providing a predictive framework to assess bearing-region behaviour in additively manufactured HSHT glass fibre-reinforced Onyx joints.

- Quantify global fibre volume fractions and localised toolpath architectures for 0, 2, and 4 concentric fibre ring configurations using Eiger build data.
- Apply Classical Laminate Theory (CLT) to establish the un-notched, global macro-mechanical baseline properties of the composite laminate.
- Develop a geometric local reinforcement framework to quantify circumferential fibre continuity bounding the hole defect. Establish an analytical hypothesis correlating localised geometric fibre continuity to enhanced local load transfer capability under complex bearing stress fields for future mechanical testing.

2. MATERIALS AND METHODS

Specimens were fabricated using a Markforged Mark Two printer. The matrix material was Onyx (micro-carbon fibre-reinforced polyamide 6) and the continuous reinforcement was High-Strength High-Temperature (HSHT) glass fibre. Specimens used a constant quasi-isotropic alternating raster matrix infill orientation to establish a quasi-isotropic in-plane baseline. To evaluate localised geometric reinforcement variations around the fastener hole ($d = 6mm$), four toolpath architectures were selected:

- G0 - Onyx Neat (Baseline): unreinforced Onyx matrix printed with standard ⁂ alternating raster infill, serving as the fully unreinforced control.
- G1 - 0 rings: quasi-isotropic fibre infill throughout (no localised concentric fibre rings).
- G2 - 2 rings: 2 concentric rings of fibre routed circumferentially around the hole
- G3 - 4 rings: 4 concentric rings of fibre routed circumferentially around the hole

All specimens maintained constant nominal dimensions of 135 mm × 36 mm × 4 mm, with a central 6 mm diameter hole located 18 mm from the top edge. As shown in Table 1, Eiger build summaries demonstrate that

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the physical volume of the reinforced HSHT GF region remained essentially constant across all layouts, with total fibre volumes spanning 13.27 to 13.33 cm³ and matrix volumes spanning 5.67 to 5.70 cm³. This isolates a total global fibre volume fraction (V_f) of approximately 70.0% to 70.1%, ensuring that any observed mechanical variations are a function of local fibre architecture rather than total material consumption ($\Delta V_f = 0.10\%$).

TABLE 1: Built Specimen Geometric and Volumetric Parameters

Configuration	Fibre volume (cm³)	Matrix volume (cm³)	Vf (%)
0 rings (G1)	13.27	5.67	70.00
2 rings (G2)	13.30	5.68	70.05
4 rings (G3)	13.33	5.70	70.10

As manufacturer datasheets lacked transverse elastic properties (E_2) for individual plies, the Inverse Rule of Mixtures (Inverse ROM) was implemented to fill the preliminary lamina stiffness matrix:

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

Using manufacturer-reported lamina properties, the input elastic constants were; $E_1 = 21$ GPa for HSHT GF and $E = 2.4$ GPa for Onyx, the transverse modulus was resolved as 6.32 GPa. These constituents were used to populate the single-ply reduced stiffness matrix (Q). Classical Laminate Theory (CLT) was subsequently applied to integrate all 40 layers through the specimen thickness ($t_k = 0.1$ mm) to determine the global extensional stiffness matrix (A): Inverting A into the laminate compliance matrix ($a = A^{-1}$) yielded balanced, global engineering constants of $E_x = E_y = 8.76$ GPa and $G_{xy} = 3.20$ GPa for the un-notched structure.

3 RESULTS

The volumetric data confirms that total fibre content remains essentially constant across all layouts ($\Delta V_f = 0.10\%$), isolating toolpath architecture as the primary performance variable. Classical Laminate Theory established a uniform global un-notched baseline stiffness of 8.76 GPa. However, the localised geometric model revealed that adding 2 and 4 concentric rings significantly increases the circumferential continuous fibre path length adjacent to the defect boundary to 56.55 mm and 138.23 mm, respectively. Increasing circumferential fibre continuity increases the proportion of fibres aligned with the expected circumferential load paths surrounding the hole. Although hoop stiffness was not explicitly calculated, this geometry provides a rational basis for improved load redistribution under bearing loading. Therefore, the analytical framework suggests that localised concentric toolpaths provide a promising strategy for improving bearing performance relative to conventional quasi-isotropic architectures. Experimental validation, including the effects of post-processing annealing, is planned through ASTM D5961 bearing testing.

4 CONCLUSION

The bearing test introduces a complex, multi-axial stress field involving localised compression, shear-out, and net-tension; standard CLT is used strictly to define the baseline elastic properties of the laminate. The local concentric model quantifies the geometric fibre continuity directly interacting with the loading pin. It's hypothesised that the increased circumferential fibre length in G3 is expected to provide a vital hoop-stress containment effect. While it may not eliminate localised compressive crushing directly beneath the pin, it is expected to significantly delay shear-out or net-tension failure modes, which will be evaluated experimentally.

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