# Effect of Fibre Microstructure on Kinking in Unidirectional Fibre Reinforced Composites Imaged in Real Time Under Axial Compression

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**Abstract**

It is well known that fibre-reinforced polymer composites (FRPs) undergo micro buckling, then catastrophic failure by kinking when loaded under compression. The aim of this project is to use x-ray computed tomography (CT) to investigate how initial fibre misalignment impacts initiation and propagation of FRP kink bands. We manufactured glass fibre/epoxy composites with intentional fibre misalignment and waviness. The misalignment angle, amplitude, and phase of the waviness are quantified algorithmically from SEM images and CT scans. This step is followed by in-situ compression captured at the European Synchrotron Radiation Facility's ID19 beamline. Previous work has shown that kinking occurs within 1.2 ms [1] and is essentially planar [2]. As such, synchrotron radiography at 40 kHz is necessary to capture the kink event while achieving the high spatial resolution needed for tracking fibre trajectories. We will focus on the contribution of in-plane waviness on damage within the kink plane, as well as the role of both in-plane and out-of-plane waviness on damage propagation in 3D.

## Introduction

The compressive strength of FRPs is known to be variable and often only 60% of their tensile strength due to sudden and catastrophic failure by kinking. The mechanism of kink band initiation and propagation has historically been controversial, though previous work by this group has used ex-situ X-ray microtomography (µCT) following uniaxial compression on unidirectional carbon-fibre FRPs to visualize the morphology of kink bands in 3D for the first time [2]. A subsequent study used in-situ synchrotron radiography at 10kHz during testing to visualize damage propagation in real time [1]. These results have shown that kink bands initiate due to fibre micro buckling. These buckled fibres can lead to longitudinal splits along the fibre direction, which open while the matrix fails under shear. The fibres are then free to bend due to the lack of lateral constraint on the fibres from the matrix. Eventually, the fibres cannot bend further, leading to kink band initiation as the fibres break and propagate rapidly across the sample. Further, sophisticated fibre tracking has been applied to tomograms collected in-situ using fast synchrotron X-ray CT to analyze the evolution of the fibre trajectories leading up to and including micro buckling [3]. This study quantified fibre orientation throughout loading and reaffirmed that the tendency of an FRP towards micro buckling is directly related to initial fibre misalignment, waviness, and other manufacturing defects. However, these studies did not capture the kink event itself due to limited scan speed; notably, [2] presents 3D images of smaller kinks formed within the main band, but extremely fast, high resolution in-situ imaging is required to elucidate the formation mechanism of secondary kink bands. Finally, [3] specifically focused on fibre trajectory changes in well aligned samples to quantify kink band formation. Given previous results, the study presented herein aims to further probe the role of misalignment and to use ultra-fast in-situ synchrotron radiography during compression to capture the kink event and related damage modes.

## Methodology and Aims

The main aim of this study is to capture the kink event and characterize damage in relation to fibre misalignment and waviness. To this end, glass fibre reinforced polymer laminates were made from nominally 12 µm diameter fibres infused with Araldite® LY 564/Aradur® XB 3486 epoxy resin. Glass was chosen because it has a greater difference in x-ray attenuation relative to the epoxy matrix than carbon fibres; greater attenuation difference allows better tradeoff in contrast/required exposure time, and easier segmentation of fibres. Nominally 2mm x 2mm x 10mm rectangular samples were cut from the laminates, notched, and mounted into chamfered steel end caps. This sample geometry was chosen so as to induce kink band formation within the field of view during CT scans and radiography, and to control the location of the kink plane within the sample.

Laminates were made via several different vacuum bagging techniques to create samples with intentional misalignment and waviness. Specifically, we have adapted the method described in described by Wisnom and Atkinson [4] in an effort to exaggerate the common effect of CTE differences between laminate and mould. We aimed to highlight this effect as it is the most common and most impactful cause of waviness in FRPs found in a systematic study conducted by Kugler and Moon [5]. A second method involved manually distressing plies before adding them to the layup in order to exaggerate the effect of random misalignment during manufacturing.

The misalignment angle and amplitude and phase of the waviness are quantified algorithmically from SEM images and from CT scans taken prior to mechanical testing. This step is followed by compression in a tension-compression rig developed by INSA-Lyon for in-situ experiments. As mentioned, kinking occurs within 1.2 ms [1] and previous synchrotron radiography at 10kHz offered insight to kink band formation but failed to capture the actual kink event. To this end, we employ high speed radiography using a beam with a mean energy of 18 keV at the ESRF's ID19 beamline. A frame rate of 40kHz is necessary to achieve the high spatial resolution necessary to track fibre trajectories, and was feasible using ID19's high flux paired with a Photron camera and the INSA rig designed for such experiments.

Finally, post-mortem CT scans are used to characterize resulting kink bands and micro bands in 3D, as well as planar fibre splits in the planes perpendicular to the kink plane. Our aim is to understand the mechanism of kink banding during FRPs compressive failure and the role of fibre microstructure on kink band initiation and over the course of damage propagation. The data is analysed to identify the following in relation to fibre misalignment and waviness:

1. Differences in fibre microstructure as a result of manufacturing
2. Contribution of in-plane waviness on kink initiation and propagation
3. Contribution of both in-plane and out-of-plane waviness on damage propagation in 3D

The results presented are radiographs of the kink band forming recorded during in-situ compression. In addition, CT scans taken before loading will be presented to characterize fibre microstructure, and post-mortem CT scans will be presented to characterize 3D damage modes.

## References


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