Response to the reviewers

The following color scheme is used in response to the reviewers:

- In blue color the response to the comments raised by the reviewers
- In yellow color the modifications added to the manuscript

Response to Referee #1

This work presents an experimental and numerical investigation into the stiffness knockdown of GFRP laminates with artificially manufactured embedded wrinkle defects. Overall, the paper is well written, easy to understand and contains valuable information. A few queries are as follows:

The authors appreciate the positive comments. We considered all the queries raised relevant to improve the quality of the manuscript. The points are addressed as follows in the manuscript:

1) It appears that the experimental/computational excercise on stiffness evaluation is carried out at a stage when no global failure mode (such as delamination) has been triggred from the wrinkle. If so, can the authors please mention this fact clearly? This is important, since if the load level triggers damage, more pronounced difference in stiffness will be seen between the 'flat section' and 'wrinkle section'.

Agree with that, here what was added to the manuscript

Prior to testing, the specimens were polished with sandpaper and treated with a lacquer Acryl spray to increase the bonding strength and attenuate the effect of rough side borders (Yang, et al. (2019)). A numerical buckling analysis was conducted to verify that the sample length within the grip section was bellow the buckling limit under compression for the target load. A strain rate of 0.01 $\%/s$ was used for three elapsed cycles. As a loading, a tension-compression test with load amplitudes of $\pm$ 16 KN was applied over an external controlled program, which feeds the machine with a triangular ramp loading. The load level is retained sufficient low in order to avoid damage initiation such as delamination at the wrinkle section. The tensile-compression strain was measured at the four channels of the clip gauge extensometer.

2) The authors have mentioned that the simplified surrogate model eliminates minute geometric details of ply folds and resin pockets, while the high fidelity model captures all these details. It would be good to include images of meshed finite element models of surrogate vs high fidelity models side by side and also compare the total number of elements . Since , the results in Figure 9 indicate that the surrogate model predictions for both type of wrinkles are very close to high fidelity models, it would be interesting to know the simplified meshing pattern that still produces an accurate results. Also, can the authors compare the computational time saving while using the surrogate model vs the high fidelity model?

The images of the finite element models were included accordingly. The changes are included as below:

4.2 Finite Element Model

The numerical simulations are conducted in ABAQUS standard version 2021, meaning that an implicit linear Newton Raphson solver is used to predict the model response. Two 2D models are obtained with geometrical parameters from the image based geometric model described in section 4.1: a surrogate model (SM) and high fidelity model (HFM) as shown in Figure 6.

The HFM embodies the geometric complexities of the characteristic defect. Thus, the HFM refers alone to high fidelity geometric features represented in the numerical model, which result in the same size of finite element degrees of freedom evaluated in few minutes. 2D 8-node plane stress elements with biquadratic reduced integration (CPS8R) are used to discretize the

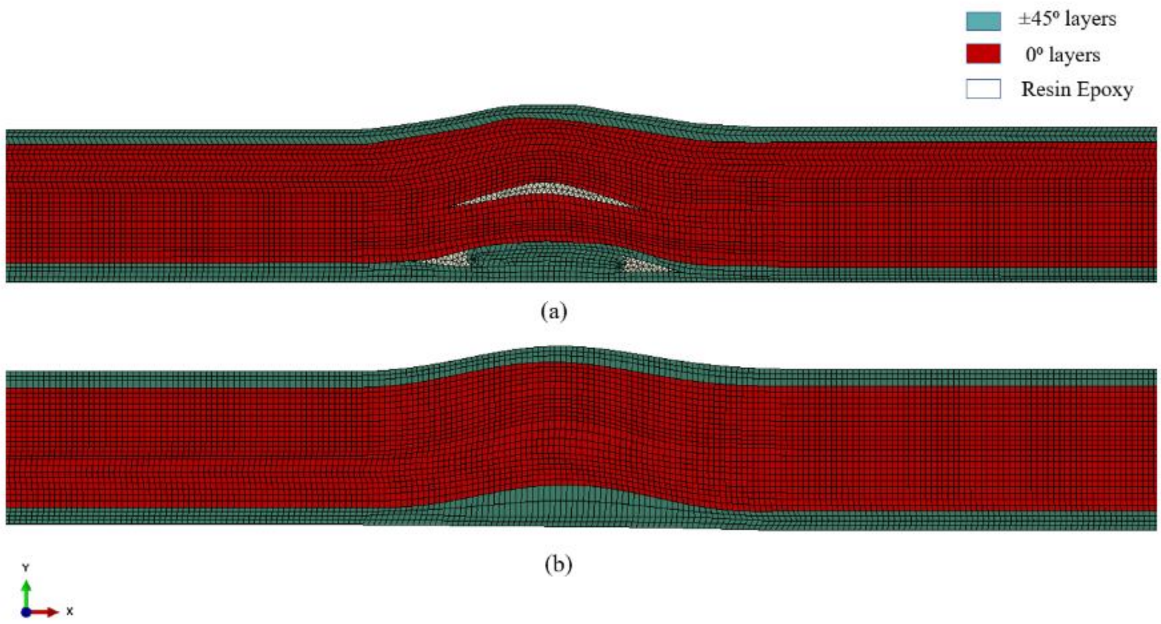

Figure 6. Comparison of mesh discretization with the geometric details of the wrinkle type 1 for the models: (a) HFM present the geometrical complexities of a fold wrinkle and resin pocket (b) SM present a simplified geometrical configuration.

3) Although shear loading in the wrinkle section and associated hysteretic loss in the resin is experimentally measured, the model does not assume any hysteretic damping effect. Can the authors suggest how their experimental finding on hysteresis loss be included in a future model development?

Indeed, at this point, the effect of the hysteresis loss is not accounted for in the model. The hysteresis loss experienced by GFRP is mainly related to the viscoelastic behaviour of the polymer matrix. The viscoelastic effect can be addressed by a material characterization including the viscoelastic properties in the model. Here is the modification in the text:

averaged. Figure 9 shows the hysteresis loop in detail for both types of wrinkle configurations and sections.

The hysteresis loss observed experimentally is mainly driven by the viscoelastic behaviour of the polymer matrix. Although not considered in the present numerical model, the viscoelastic effect can be addressed by using a visco-material law. The damping is calculated by averaging the hysteresis loop area over the three reversal cycles. The wrinkle section experience higher energy

Anonymous Referee #2

1) General: A good methodology and for the most part good and well-founded. The relatively small deviations also indicate a good simulation and the correct assumptions. The quality of the documentation can still be improved. The evaluation could be more precise. The material map is "strange" and the methods at the Matlab script call. Adapt the pictures accordingly.

The authors appreciate the positive feedback. We considered all the points raised as a suggestion to improve the quality of the manuscript. The reply below refers to the comments that require a detailed explained response, whereas the minor corrections were modified straight in the text and highlighted in the pdf version submitted. The points are addressed as follows:

2)Please define the terms (wrinkles, fibre waviness, out-of-plane-wrinkling) more precisely. Wrinkles is equal to out-of-plane fibre waviness (see definition in Thor and Hallet 2020).

Thanks for this suggestion. This has been addressed in the following sentence:

1 Introduction

Wrinkles are manufacturing induced defects, which can impact the production cycle time leading to expensive repairs when required, ultimately resulting in a decline of wind turbine blades reliability. This study is dedicated to evaluate out-of-plane wrinkles due to its critical impact on the structural performance of the blade. Thus, the term wrinkles in this study are interpreted as out-of-plane wrinkles Out-of-plane wrinkles is a result of fibre bending out of the laminate and layer bending through-thickness (Wang, L. (2001), Lightfoot, et al. (2013)). Ply/fiber waviness is a fiber deviation from a straight alignment in a unidirectional laminate (Thor, et al. (2020)).

3) If you want to keep the picture, please mark the place where it was taken in the cross-section on the left. Does it come from type 1 or 2 or from a place where both types look the same? Also scale indication of the plies-position to the respective position in the image

The suggestion was considered, here is the modification:

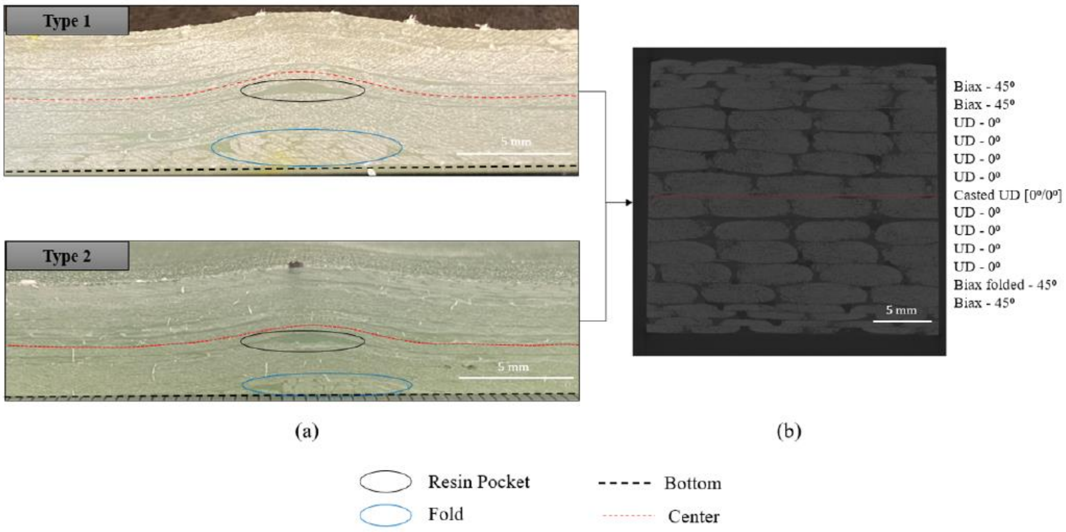

Figure 3. (a) Types of wrinkle configurations selected for the analysis; (b) Layup specification for the transverse cross section of the specimens taken at the flat region analogous to wrinkle type 1 and type 2 .

4) Table 2: for the UD layer, the same value is taken for all shear moduli, but the transverse contraction number is not. With BD, the shear modulus is varied and also the shear contraction coefficient. What material behaviour is assumed? Where do the characteristic values come from?

The 23 values have a neglected influence on the actual longitudinal stiffness of the model. The characteristic values were derived in a research project which hasn't been published yet.

5) Method for filtering outliers very superficial. Name method of fitting technique (third step) - in the text it says polynomial was tested and in Figure 5 it says Fourier. Figure 5: Insert steps from text, numbers and font in diagram not recognizable. Where does the difference between the two models (surrogate & high fidelity) come from when the same steps are run through? How is the area described in the simplified model? - A picture would be desirable. Could this be made clear in the picture?

The authors combined the image processing toolbox available on Matlab with a series of encoded scripts to perform image processing, filtering, segmentation and fitting of each individual fiber. The filtering technique of the wrinkle image is based on rank filtering/median filtering, which removes outliers without reducing the resolution of the image. When it comes to the fitting technique, each individual fiber is evaluated accordingly to the least residuals which rule the best fit type adopted. Figure 5 was modified accordingly. The high fidelity model differs from the surrogate model in terms of geometrical features represented. That difference is explained in detail in section 4.2, where the difference between both models can be seen in Figure 6 of the updated manuscript version.

Modification is done accordingly as follows:

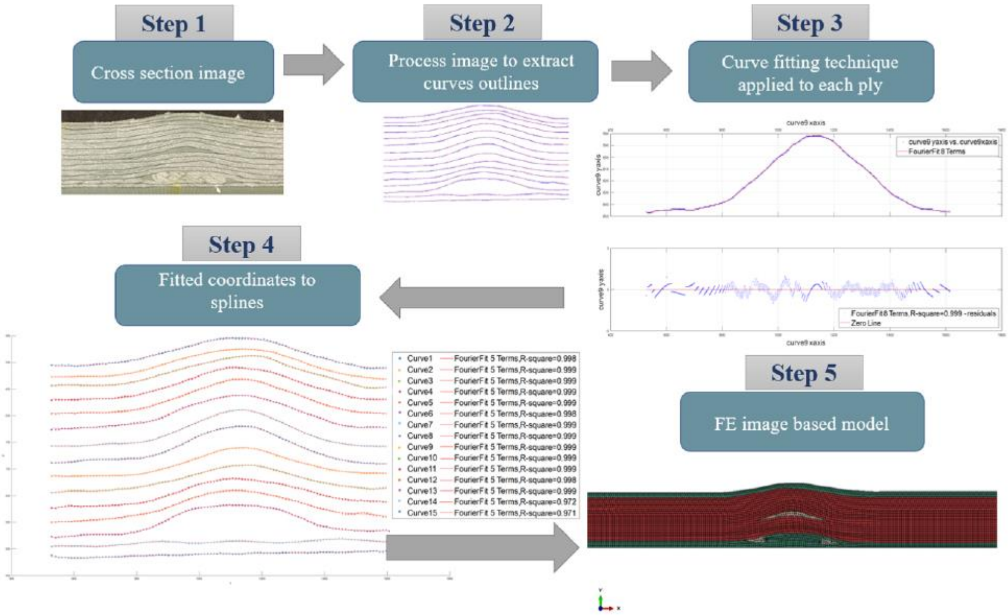

Figure 5. Four-step sequence to translate the cross section defect profile into a finite element model by thresholding individual contours, segmentation of such contours and outliers removal, mathematical fitting techniques to generate even spaced coordinates and finally the extraction of 2D coordinates to import into ABAQUS.

For each defect configuration, two types of finite element models are derived: a surrogate model and a high fidelity model. The surrogate model solely accounts for the effect of individual ply waviness disregarding the effect of complexity geometry resultant from the fold in the Biax ply and resin regions. The high fidelity model regards the effects of resin regions and asymmetric wrinkle shapes resultant from the s-shaped Biax layer. The detailed finite element model is presented in Section 4.2.

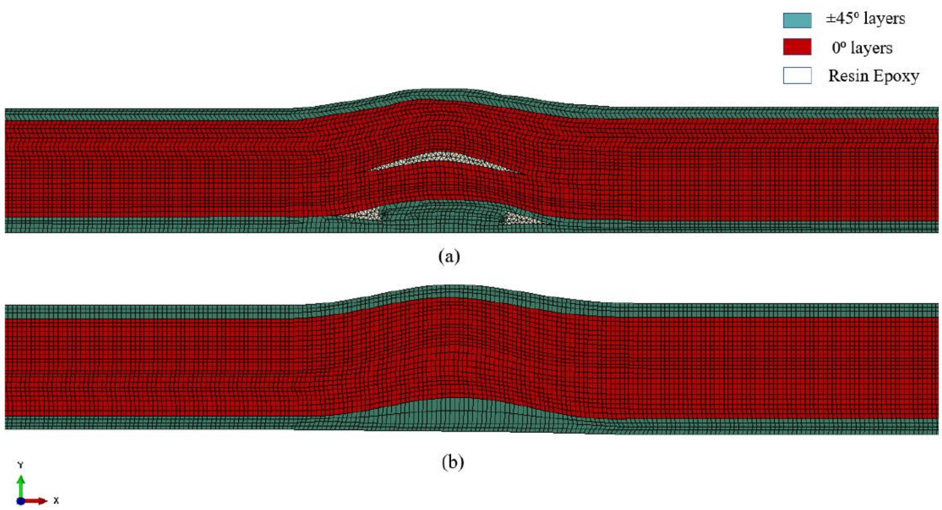

Figure 6. Comparison of mesh discretization with the geometric details of the wrinkle type 1 for the models: (a) HFM present the geometrical complexities of a fold wrinkle and resin pocket (b) SM present a simplified geometrical configuration.

6) Please, explain why the amplitude was chosen? Is a load-dependent increase in material damage to be expected at 16 kN?

In this study, the samples were not driven to failure and the load was kept sufficiently slow to perform only stiffness measurements.

7) the yellow colour is difficult to see:

Change made accordingly below:

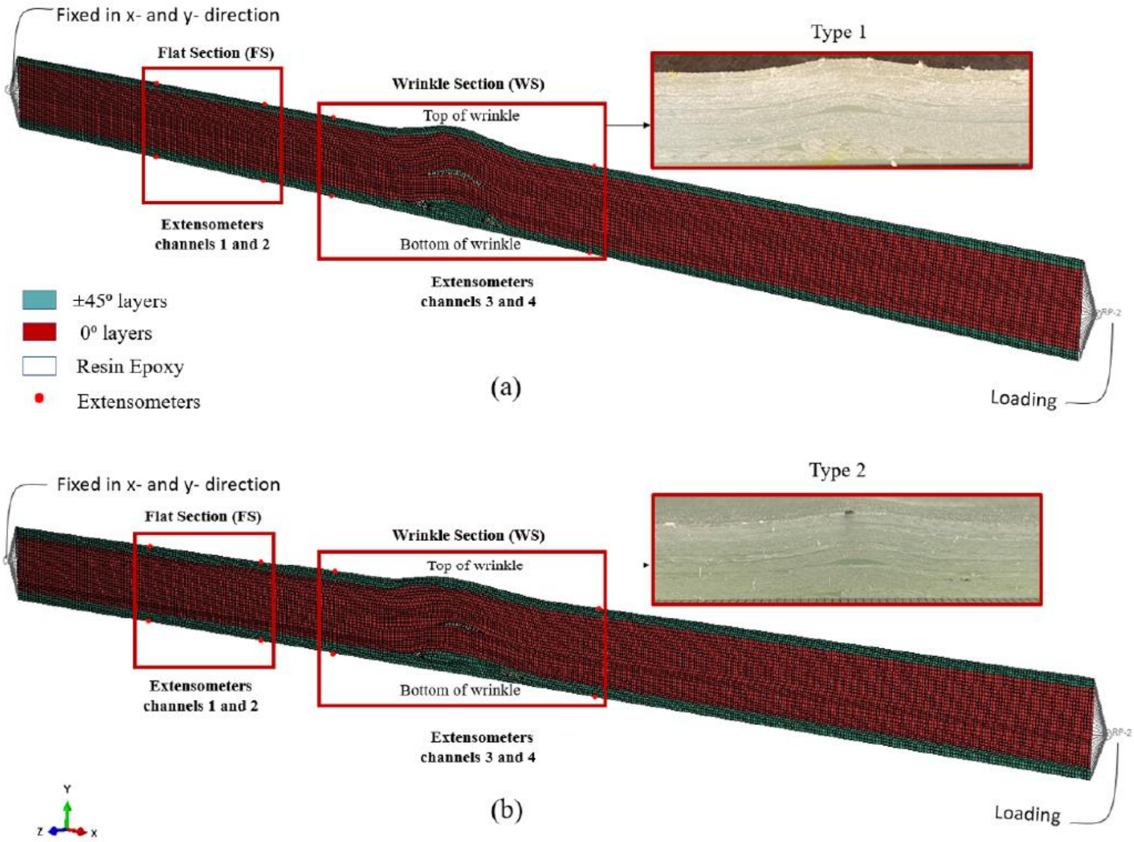

Figure 7. High fidelity finite element model modelled in a ply-by-ply sequence, with biaxial layers on top and bottom, UD layers in between and resin pocket around the biax fold and underneath the ply contour of max. amplitude : (a) coupon specimen model for wrinkle type 1 (b) coupon specimen model for wrinkle type 2.

8) Please, explain why the amplitude was chosen? Is a load-dependent increase in material damage to be expected at 16 kN?

Modification done as follows:

strain rate of 0.01 $\%/s$ was used for three elapsed cycles. As a loading, a tension-compression test with load amplitudes of ± 16 KN was applied over an external controlled program, which feeds the machine with a triangular ramp loading. The load level is retained sufficient low in order to avoid damage initiation such as delamination at the wrinkle section. The tensile-compression strain was measured at the four channels of the clip gauge extensometer.

9) model prediction for flat section is better on tensile side opposite to compression side. And the other way round for wrinkle section. Can you explain these?

Explanation updated in the manuscript as follows:

the flat section, 40 mm away from the wrinkle center with an extensometer gauge length of 25mm. The results obtained from the numerical models are extracted at the same position as the experiments. wrinkles are introducing an assymmetry in the experimental setup. The difference in stiffness in tensile and compression side will depend on details on how the samples are clamp and alignment of the pistons. Therefore we are mainly focused on averaging the stiffness at the two sides what is done subsequently in the comparison.

10) Evaluation and comparison actually good. Good reasoning why the FS differs for both types of same trend. But how can the differences in the models be explained if everything has to be the same there (similar assumptions)? According to the type 1 statements, I would expect a similar trend to come out on the WS side for type 2. However, the "rough" model is better. Why?

Thanks for pointing that out. When it comes to experimental data, the flat section differs in results for type 1 and type 2 as the samples might deviate in fiber volume fraction of potential microcracks that can arise during the manufacturing process. As it comes to the difference in the model, that cen be due to the slight difference in thickness for each type of wrinkle which was taken into account in the model. The difference from the surrogate and the high fidelity model for the flat section it can be due to slight differences in the mesh as the size of the mesh changes locally for the HFM due to the complex pattern of fold and resin epoxy.

10) Results of experiments in FS section should be the same for type 1 and 2?

Below the authors try to explain that in the manuscript:

lations of FE simulations and the results from experimental tests. When it comes to experimental data, the stiffness at the flat section has a minor deviation comparing type 1 and type 2 configurations as the samples might deviate in fiber volume fraction or potential microcracks that can arise during the manufacturing process. When the deviation is observed in the numerical results, that is in principal due to a slight difference in thickness for each type of wrinkle which was taking into account in the model for both types of samples. Furthermore, the complexity of the geometrical features present in the HFM induce a different pattern of mesh where the local size of few elements are different from the SM which is simpler and therefore straigthfoward for a even sized mesh.