

## Experimental and numerical analysis of the head tube joint strength

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**Abstract.** A composite bicycle frames are produced by a variety of technique and the joint of tubes is weakest link for tube to tube design. The FE model of the joint was created and the joint strength was experimentally verified when the load was monitored by strain gauges the DIC and Acoustic Emission method.

### Introduction

The bicycle frame is designed with regard to performance and durability. Composite materials have brought new possibilities to change the frame properties like stiffness and mass. A wide range of composite materials and their manufacturing technologies exists, which might lead to different designs with different frame stiffness, strength and price. The paper is focused on one of possible frame designs, where the frame is built from structural tubes with lamination over the tubes in the joint areas. In this type of the design, the joints of the tubes are the weakest points. The experimental verification of the head tube joint strength under typical loading state with numerical calculation validation is included in this paper. The load of the joint was monitored using a strain gauge and the Digital Image Correlation (DIC) and the damage was monitored by Acoustic Emission (AE) method.

### Composite Frame

A composite bike frame was produced by a Czech company Festka using composite tubes by a filament winding technology as the main structural material. The manufacturing technology enables to tailor the frame to the customer's specific requirements. The tube to tube manual lamination method is used to made the frame from the tubes. Carbon fabrics and tapes together with microballoon epoxy are used in the joints manufacturing. The strength of the joint with respect to the manual production had to be verified. For the experimental verification, the head tube joint was selected as the most stressed. For this purposes, simplified frames containing the main triangle of frame were made and tested, see Fig. 1.



Fig. 1: Simplified composite bicycle frame

## Experiment

The horizontal force head-tube test [1] was used to obtain the critical failure load of the frame and of the head tube joint. A loading device was designed where the frame is fixed in place of the bottom bracket and loaded with a fork replacement connected to servo hydraulic actuator IST PL63, see Fig. 2. The loading was carried out by position control until specimen failure. All devices were synchronized with the force signal during the test by means DC output from hydraulic actuator control unit.

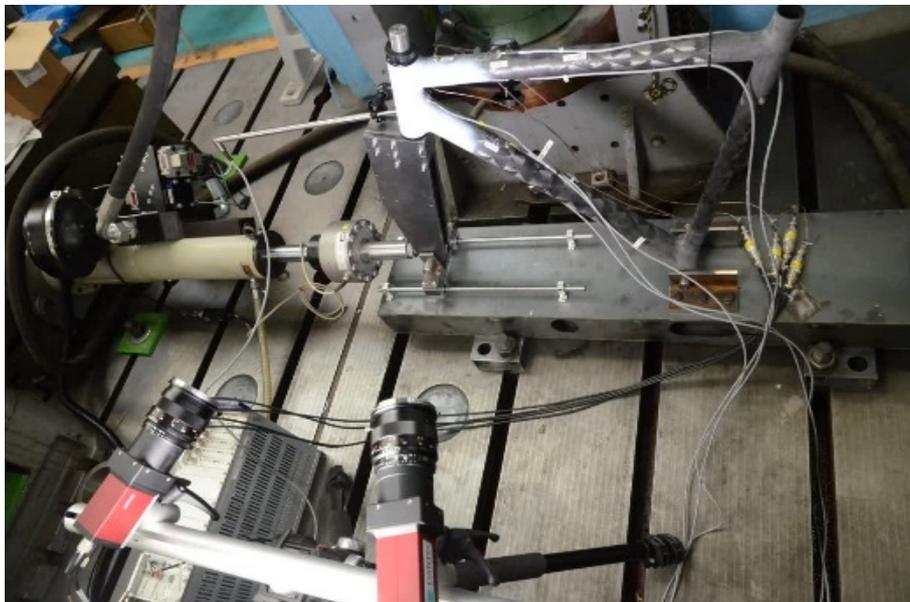


Fig. 2: Experiment setup

Record of experiments can be seen in Fig. 3, when on y-axis is normalized force and on x axis is displacement.

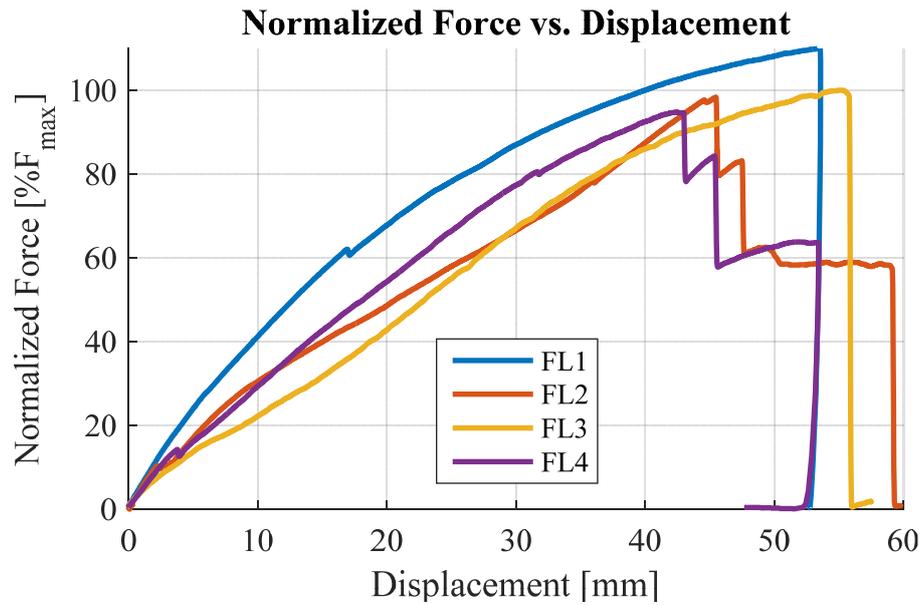


Fig. 3: Tests records normalized force vs. displacement

**Strain Gauge measurement.** Experiences from the previous tests demonstrated, that the dominant loading is the bending stress in the frame plane. Therefore, strain gauges were only installed in this plane to monitor the stresses around the joint. Two strain gauges were installed on the top tube (TTF) and two on the down tube (DTF). Another strain gauge was installed in the back of the head tube (HT). Standard strain gauges with resistance of 350 Ohms and methylmetacrylate cold curing glue was used. Measurement unit HBM Spider8 was used for data acquisition with quarter bridge connection.

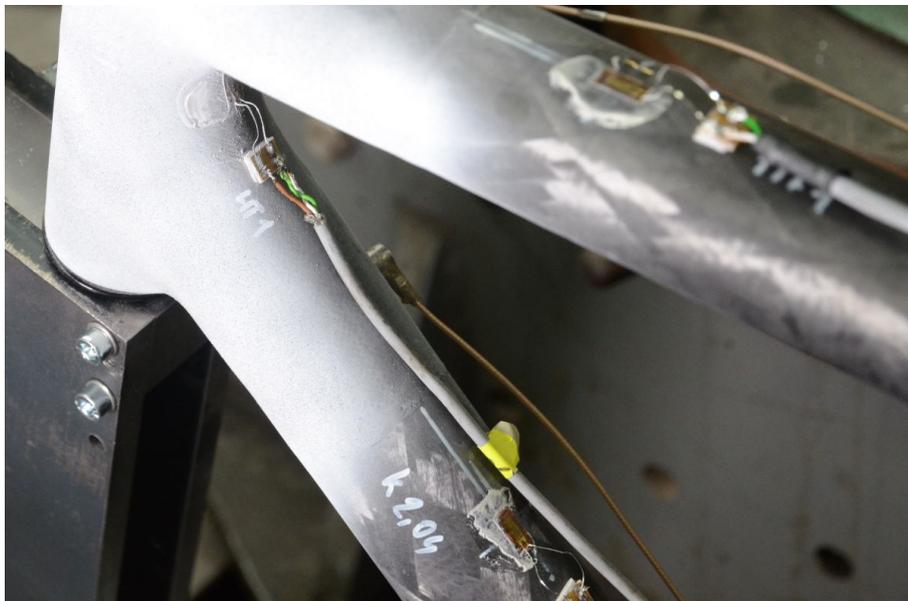


Fig.4: Strain gauge installed on the specimen

An example of evaluated data for one sample can be seen in Fig. 5, where tension and bending signals on down and top tubes were separated. Initialization of the primary damage is evident on the record of strain from HT strain gauge at the level of two thirds of maximum force.

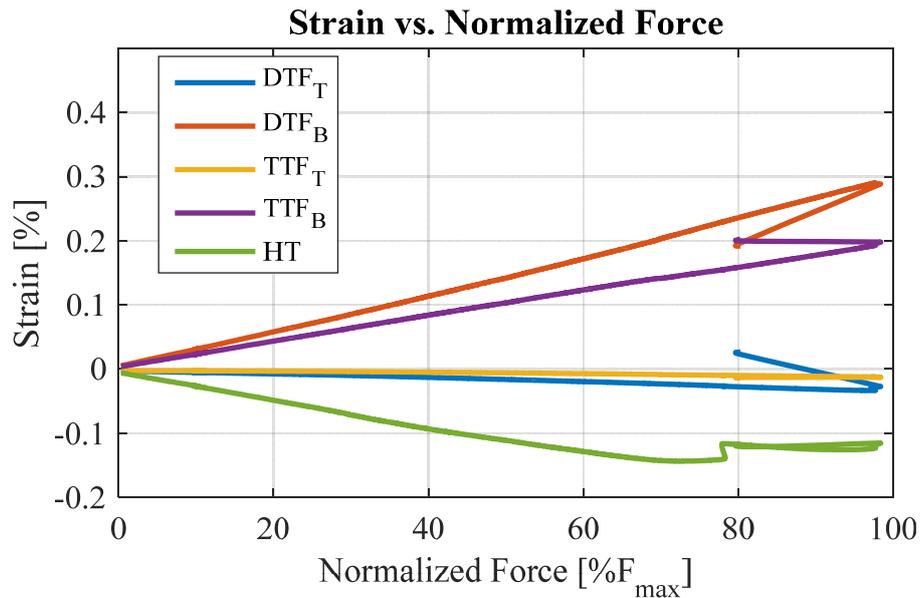


Fig. 5: Tests records strains vs. normalized force

**Digital Image Correlation.** Area information about displacements and strain was obtained using DIC, where an irregular black and white pattern was made by airbrush on the side of the joint, see Fig. 4. System Q400 with 16Mpx firewire camera was used for image recording and software Istra 4D software from Dantec Dynamics for evolution. Principle strains on joint can be seen in Fig. 6, when load level is maximal force.

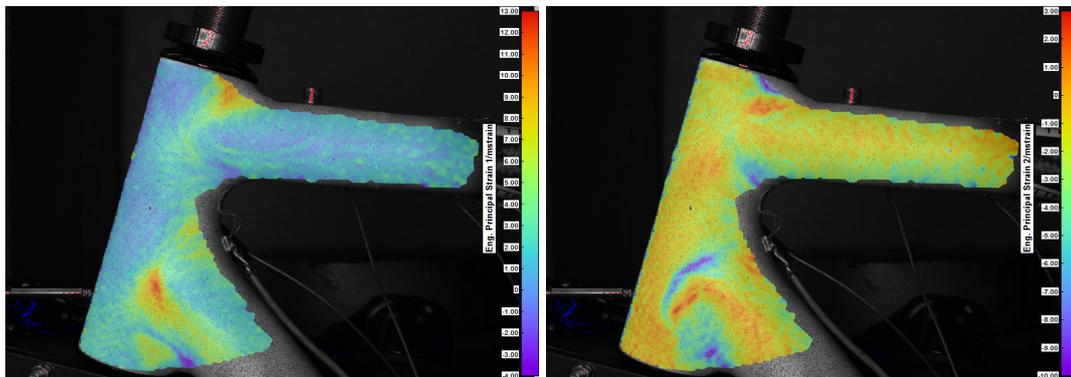


Fig. 6: First (left figure) and Second (right figure) principle strains maximal load level

**Acoustic Emission method.** AE was used to track damage during strength testing. Three sensors were installed in the vicinity of the head tube joint. One on the side of the top tube, one on the side of the bottom tube and one on the side of the head tube, see Fig. 7. Measurement unit Xedo with software was used for event recording. An example of AE event recording is in Fig. 8. Initialization of the initial damage is evident from the increase of AE events again at the level of two thirds of maximum force.



Fig. 7: Location of AE sensors

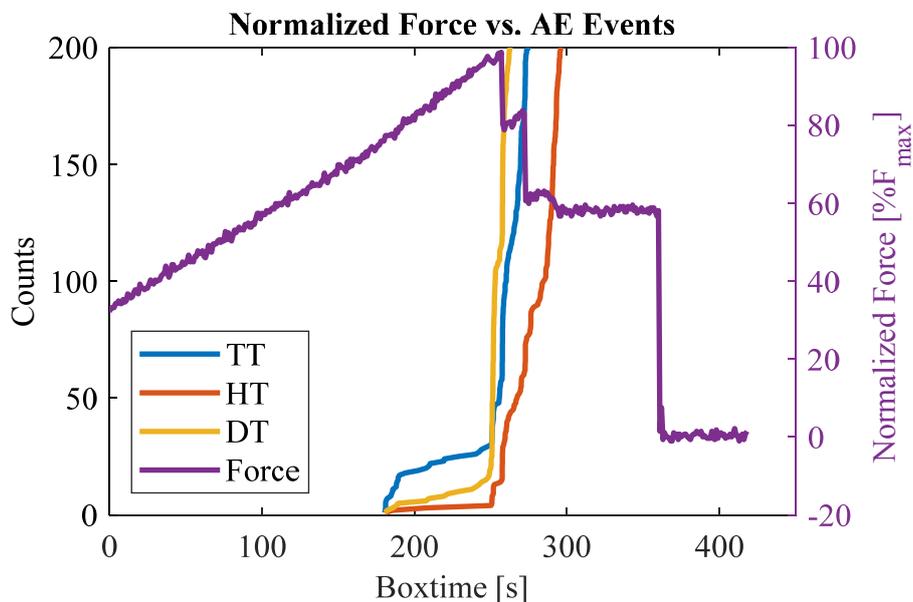


Fig. 8: AE events record

### Numerical Simulation

The experimental loading of the composite frame was simulated using finite element analysis. The goal was to predict the frame strength using the finite element analysis and to verify the strength and stiffness behaviour of the model with the experimental results. For the simulations, ANSYS software was used with ANSYS Composite Prepost (ACP) toolkit. The FE model of the frame was made of a head tube; a top tube; a down tube, a seat tube and a bottom bracket tube, see Fig. 9 (left). These tubes were modelled using solid-shell elements (SOLSH190). The head tube joint lamination was modelled using a classic conventional shell element (Shell181), see Fig. 9 (right). The tubes and lamination were connected using “MPC bonded” connections. The fillers in the tube connections were modelled using solid elements.



Fig. 9: Geometry of the bike frame model with the detail of the head tube joint shell elements.

The joint lamination, which is critical to the frame strength, was composed of uni-directional carbon fibre plies and woven fabrics combination. The laminate sequence was quite complex, as the joint lamination was made of more than 10 types of layers with a completely different fibre orientation. Two examples of the uni-directional plies of the lamination are given in Fig. 10. Each UD and fabric ply of the lamination was input using ACP, which enabled to have a full laminate specification with one shell through the joint thickness only without any major simplification of the each ply fibre directions.

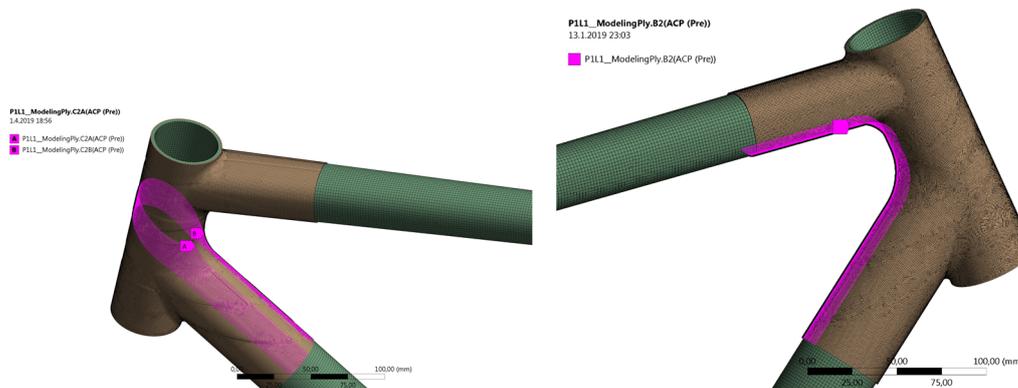


Fig. 10: Examples of joint plies definition in the shell model of head tube lamination.

The goal of the model was to evaluate the frame stiffness and strength. A linear static analysis was used for those purposes. The composite strength was established using a first ply failure analysis. The first ply failure analysis is using the failure index, which is computed as the response to the given loading using the specified composite strength criterion. When the failure index (0 for not-loaded coupon) reaches the critical value (1.0 or higher), the first ply failure criteria indicates the failure of the investigated ply and therefore the failure of the design. However, it must be noted that the first ply failure does not have to indicate the global behaviour change in terms of strength or stiffness. It indicates the end of linear elastic behaviour, however, the indicated failure does not have to be the one, which is causing the major failure.

The failure index was computed for each ply and fabric of the lamination. For the evaluation, following criteria were used: Maximal stress; Tsai-Wu; Tsai-Hill; Puck. The strength data of plies and fabrics were taken from the experiments (tensile strength) or as a nominal data from the literature [2].

The model was loaded by a concentrated force, see Fig. 9 and for this loading the failure indexes through the thickness of the lamination were evaluated. The maximal value was detected at the bottom of the head tube – down tube joint, see Fig. 11. The position of the maximal loading is consistent with the experimental results as the failure during the experiment started at the down-tube – head-tube connection, see Fig. 12, and then continue through the lamination to the top-tube – head-tube connection.

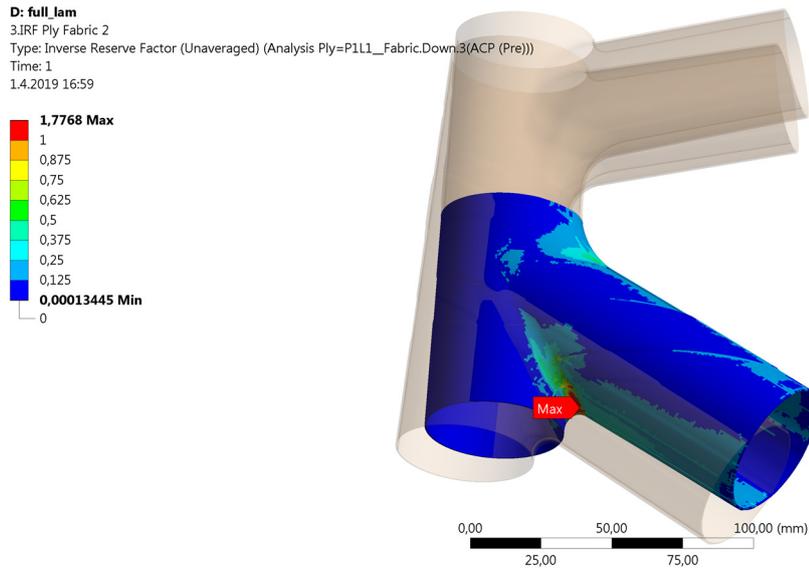


Fig. 11: Maximal failure index in the composite lay-up of the joint lamination.



Fig. 12: The down tube-head tube failure during the frame loading.

## Results

The comparison of the numerical model and the experiment can be seen in Fig. 13, where the dependence of the head tube displacement versus normalized force is plotted. The graph for the numerical model ends at a point corresponding to the load when the critical value of failure index was reached. A good match of the FEM model stiffness with the obtained experimental values is evident. The first frame damage detected by the strain gauge signal on the head tube and the increase in the AE event amounted to about two-thirds of the maximum force. The load level at which the failure index value was reached in the FEM model is two-thirds compared to the average force at which the first damage was detected experimentally.

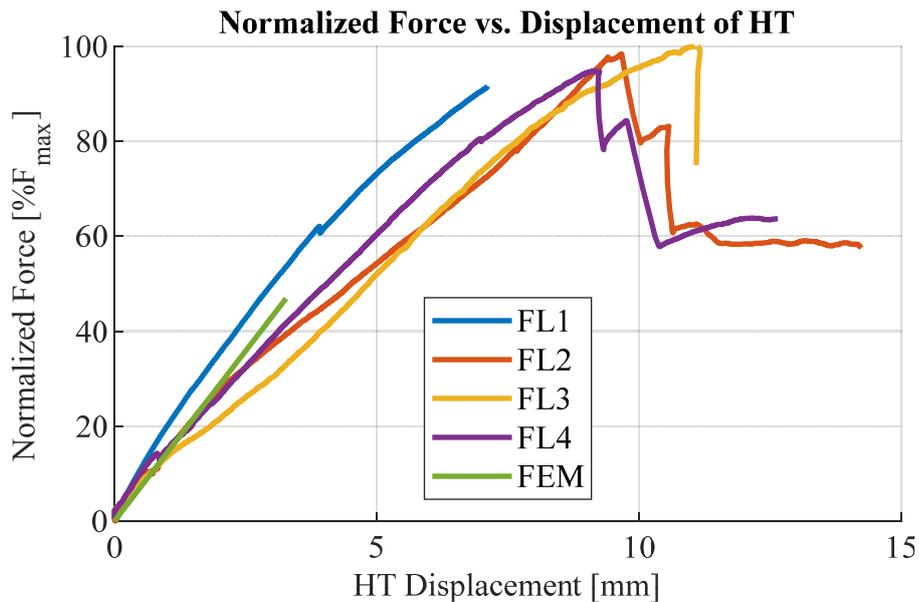


Fig. 13: The down tube-head tube failure during the frame loading.

## Conclusions

Suitably positioned strain gauges together with AE sensors are capable of detecting primary joint damage. DIC allows to get a more complex area information of tube joint loading. A good agreement of the experimental results with numerical calculation was confirmed. The numerical model can be used with a high level of credibility for other tube joint variants.

## References

- [1] ISO 4210-5:2014 Cycles -- Safety requirements for bicycles -- Part 5: Steering test methods. ICS : 43.150 Cycles 2014. International Organization for Standardization.
- [2] Ever J. Barbero. Introduction to Composite Materials Design, 2<sup>nd</sup> edition. CRC Press, 2010, ISBN 978-1420079159.