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Development of composite element joining keel beam and aircraft fuselage

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Presented document deals with design, stress/strain analysis and testing of composite element used in aircraft for joining keel beam with fuselage. Nowadays this part is made from titanium because of electro-chemical corrosion which can occur when joining steel and composite material. Titanium T profile is manufactured from the block which is not economical because much waste material during machining. That´s why two composite elements of T and Y shape were designed. These profiles were manufactured from C/PPS fabrics with the use of thermoforming technology.

At first stiffness comparison of both composite profiles and titanium one was done. With the use of FE software Abaqus models were created and loaded with unit loading through the holes in the profile´s web, see Fig. 1. Many versions of the computation were done e.g., rigid vs. deformable plate, effective characteristics for composite profile vs. lay up characteristics, solid vs. continuum shell elements, etc… with the result that Y-profile is stiffer than T profile.

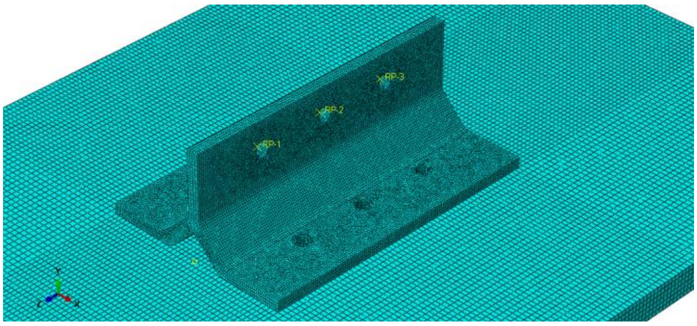

Fig. 1. Model of C/PPS Y profile

Next step was the proof that both profiles can transmit the real load of the component which was given to us from the manufacturer. Geometry of the models was the same as in stiffness analysis but just models with layered continuum shell elements were used for analysis. Real load of each reference point can be seen in Table 1. Results were compared with the use of failure index (FI) evaluated by strength theories for composites in Abaqus (max stress, max strain, Tsai – Hill, Tsai – Wu, ….). Failure index can be listed for each ply or as an envelope of worst cases through plies. FI according to Tsai – Hill theory for T – profile can be seen in Fig. 2.

Table 1. Comparison of deflection/rotation for designed versions

Reference point no.	F_x **[N]**	F_y **[N]**	F_z **[N]**
RP – 1	-276.1	-411.9	3 496.9
RP – 2	-345.6	-518.9	3 007.8
RP – 3	-168.0	-415.7	2 846.1

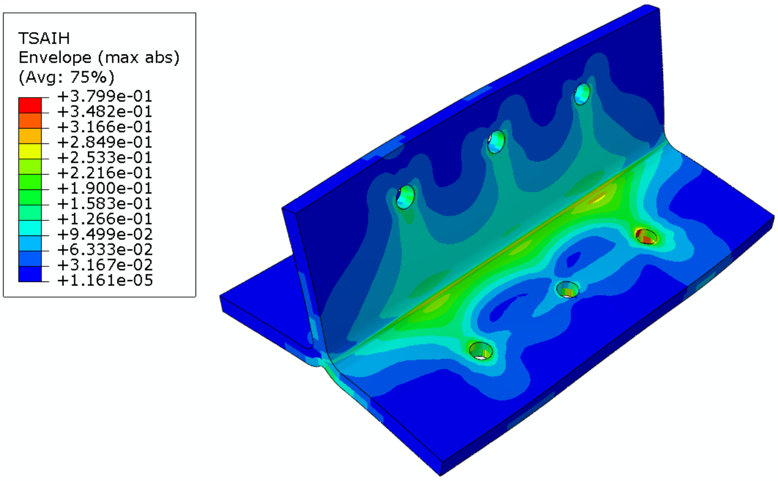

Fig. 2. FI acccording to Tsai-Hill theory for T – profile

For each tested case (T - profile and Y – profile joined with rigid/deformable plate) and each strength theory, FI was lower than 1 which means that the construction didn´t fail and it can withstand required load.

Then both profiles were experimentally tested on TIRA 2300 universal testing machine in our lab. The tensile load was applied through the screws in the web of the element jointed with the machine's jaws. The load was released just in the z direction, as shown in Fig. 3, left. The profiles were tested until total failure, but some of them were tested only until the first failure occurred (the first visible peak in the loading curve). Typical load curves for a T-profile and for a Y-profile are displayed in Fig. 3, right.

The profiles with the first failure were analysed using a CT scan and a microsection photo to find the failure area, see Fig. 4, left.

Because the real geometry of both profiles differs little bit from the ideal one, analysed by FEM in previous step, the new simulation of both profiles was carried out to analyse the location of the first failure and compare it with the failure area from CT scan mentioned above, see Fig. 4, right. The failure was interlaminar, so layered solid elements were used in the model to determine S33 stress. The first failure force of the experiment corresponds to S33=33 MPa, as calculated by FEM. The tensile strength in the 90° direction of the UD material is 39 MPa, according to the datasheet [3]. Even though it is not exactly the material used in the project, the agreement between simulation and experiment is quite good. The area of the failure from the CT scan is also in good agreement with the maximum stress area from the FE simulation.

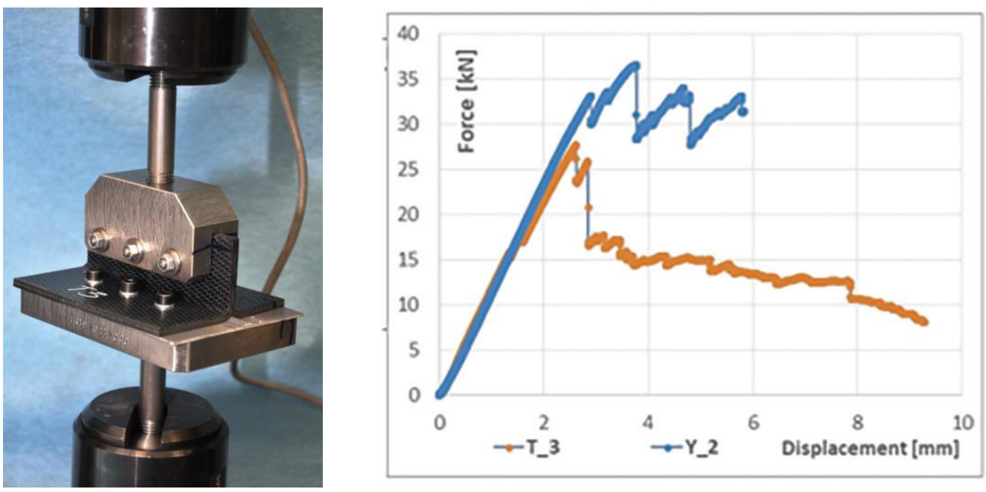

Fig. 3. T – profile loaded in tensile machine and typical loading curve for both tested profiles

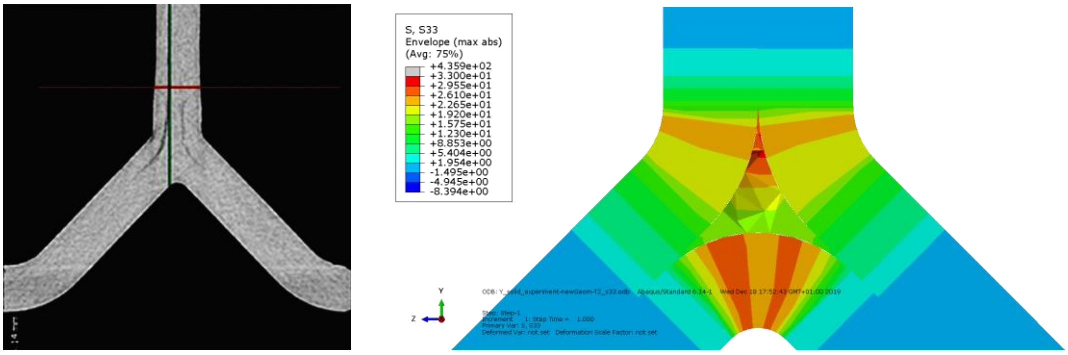

Fig. 4. First failure area evaluated from a CT scan and area with maximum stress from FEM [1]

Comparing the results from the T-profile experiment and from the Y-profile experiment (Fig. 4, right) shows that the first peak of the loading force (which is crucial for fatigue) in the tested T-profiles occurs at about 15 kN. In the Y-profiles, this peak is at about 29 kN, i.e., the improvement is almost twice as much as for the T-profile. T – profile weight 0.129 kg, Y – profile 0.127 kg. Compared with original titanium solution which weights 0.308 kg, it is around about 58 % weight saving [1].

The last step was the fatigue/lifetime tests which were conducted in the laboratory on three T profiles and three Y profiles. The *R* value was 0.1 and the frequency of the load was 5 Hz except for sample Y_03 with a frequency of 4 Hz. Sinusoidal type of signal and load control was used in the testing program. The experiment was performed using the Instron 40 kN hydraulic testing system. The selected loading levels were derived from the limit load, which was 5 910 N in the z direction – 100% meant loading up to the limit load level, 153% loading up to the ultimate load level, 200% loading up to twice the limit load level and 306% loading up to twice the ultimate load level. Once the sample was subjected to 1 000 000 cycles without failure, the experiment was stopped, and the sample was inspected by means of the ultrasonic testing method. The sample was then put aside for subsequent static testing aimed at proving whether a change had occurred in terms of the strength compared to the "virgin" samples that had been statically tested previously. The results and a description of the fatigue/lifetime test are provided in Table 2 [2].

Table 2. Lifetime results for the tested profiles

Sample	**Load level**	***F* [N]**	**Number of cycles *N* [-]**	**Result**
T_01	100%	5 910	1 000 000	without failure
T_02	100%	5 910	1 000 000	without failure
T_03	153%	9 042	1 000 000	without failure
Y_01	153%	9 042	1 000 000	without failure
Y_02	200%	11 820	1 000 000	without failure
Y_03	306%	18 085	122 396	failure

Sample Y_03 was destroyed after 122 396 cycles following the destruction of the screws (after 83 407 cycles and 108 876 cycles), which were replaced both times. Moreover, the final failure (see Fig. 5) was also accompanied by the destruction of some of the screws.

The T-shaped samples and samples Y_01 and Y_02 survived the fatigue testing process, thus presenting the opportunity to perform static testing aimed at proving whether there had been a change in their behaviour. The static testing was conducted in a similar way to that described above. The comparison of these values with the values for the "virgin" samples (Fig. 6) indicated that the values were not significantly affected by the fatigue effect.

While fatigue/lifetime testing using a small number of tested samples provides some room for doubt, it must be stressed that the testing was performed at a high loading level of up to

1 000 000 cycles. All the T-shaped samples withstood the limit and ultimate upper loads without failure. Hence, the Y-shaped samples were tested directly up to the ultimate load, twice the limit load and twice the ultimate load, which is unusual for this type of construction.

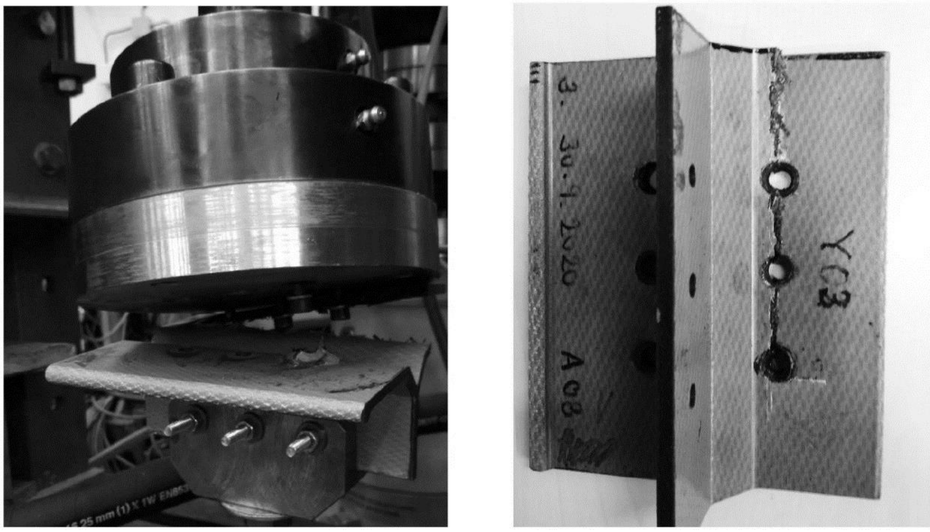

Fig. 5. Destroyed sample Y_03 after 122 396 cycles [2]

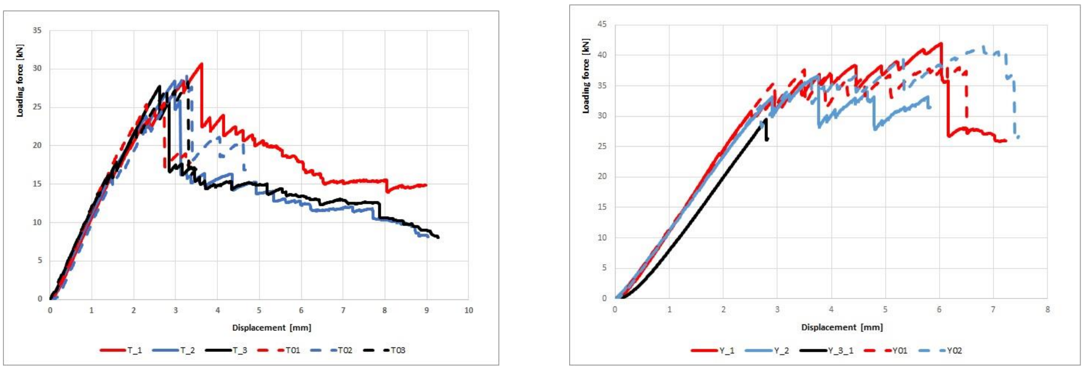

Fig. 6. Relationship between the loading force and the displacement for the tested T and Y profiles (“virgin” and after 1 000 000 cycles) [2]

The main aim was to determine the limits of the components. The destruction of the bolted joint occurred at twice the ultimate load level. These results exceeded the requirements for this type of construction. Moreover, the static testing of the samples after 1 000 000 cycles indicated the absence of the fatigue effect on the maximal loading force and force values, which corresponded with the first discontinuity in the loading diagram, compared with the “virgin” samples [2].

Acknowledgements

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[3] Toray Data Sheet for material Cetex® TC1100.