DESIGN PARAMETER STUDY OF A CFRP T-JOINT UNDER OVERPRESSURE CONDITIONS DUE TO BALLISTIC IMPACT

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Abstract
Out-of-plane loading on composite T-joints may result in catastrophic failure of the structure. In this article a numerical parameter study on the mechanical response of composite T-joints subjected to out-of-plane tensile loading is performed using LS-DYNA. The influence of both, material parameters (mode I fracture toughness and stiffness of the filler material) and geometric constraints (curvature, overlap length) on the strength of the joint is quantified. Suggestions for an optimal T-Joint design are made.

1. Introduction

Hydrodynamic Ram (HRAM) is a threat to liquid filled containers (e.g. aircraft fuel tanks) subjected to high or hypervelocity impact loading [1,2]. If a high energy object hits the skin of a liquid filled container, a shock wave is induced into the liquid. When the projectile travels through the liquid, a cavitation bubble is formed behind the foreign object causing high pressures inside the liquid filled structure. These high pressures may result in catastrophic failure of the structure as it occurred during the Concorde accident in 2000 when a piece of metal left from another plane hit the wing of the Concorde F-BTSC. Modern aircraft wings employ carbon fiber reinforced composites (CFRP) due to their excellent mechanical properties and the associated potential for lightweight design. A typical structure inside these wings is a T-joint connecting the skin to spars or stiffeners. The typical failure of these structures subjected to tensile or tensile/bending loading is delamination between the skin and the stiffening element. Consequently, in the past there has been some empirical work to improve the resistance of composite T-joints to delamination by design [3], or by through-thickness reinforcements [4,5]. This paper goes beyond empirical improvements to composite T-joints and assesses the influence of several geometrical and material parameters on the overall performance of composite T-joints by means of numerical simulation.

2. Structure under investigation

The baseline structure under investigation is the same composite T-joint used in the work by Heimbs and co-workers [4,5]. In its initial state the joint comprises of a CFRP skin, thickness 7 mm and layup $[0°/+45°/90°/-45°/0°/-45°/90°+45°/0°/+45°/90°/-45°/0°/90°]_s$, a CFRP flange, thickness 4 mm and layup $[+45°/0°/-45°/+45°/-45°/+45°/0°/-45°]_s$ and a braided filler

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between the flange and the skin. The whole T-joint is infiltrated in one shot using Hexcel HexFlow® RTM6 epoxy resin. Details on manufacturing of the joint can be found in [4]. In Fig. 1 shows the structure of interest. In the baseline experiments, the T-joint was clamped at the holes seen in the skin and pulled in tension using the holes in the flange.

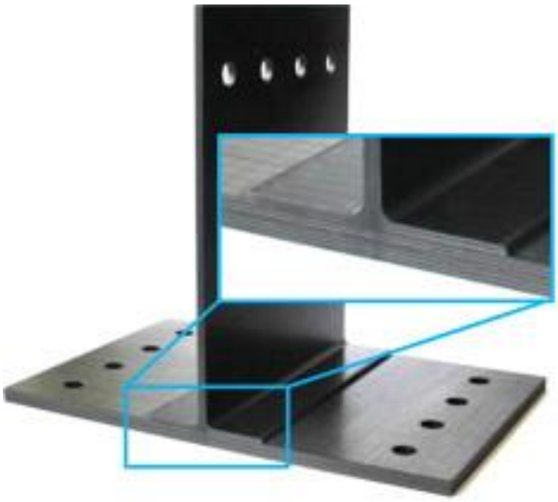

Figure 1. CFRP T-joint under investigation (from [4]).

3. Modeling approach

A finite element (FE) model of the CFRP T-joint was built for the commercial FE code LS-DYNA. Each ply is modeled individually with one single under-integrated 8-noded finite element over the thickness as shown in the detail view shown in Fig. 2. In order to reduce the calculation effort only a slice of depth 1 mm was modeled. Zero-thickness cohesive interface elements were located in the interfaces between spar and skin, skin and core, spar and core as well as the mid-plane of the spar.

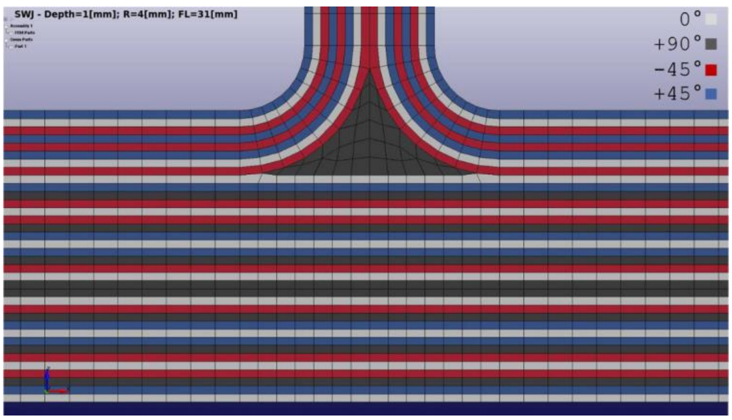

Figure 2. Detailed view of finite element model.

Following the recommendations by Harper and Hallett [6] the length of the numerical cohesive zone, for the given material was calculated to be 2.345 mm in mode I and 6.484 mm in mode II loading conditions. In order to ensure a minimum of 3 interface elements within the cohesive zone, an element

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length of 0.75 mm was used in the vicinity of cohesive interface elements. The element length for elements located in regions without cohesive interface elements was 1.0 mm. Tables 1 and 2 summarize the in-plane and cohesive material properties used for the simulations.

Table 1. Reference in-plane properties used in LS-DYNA simulations.

Density (kg/mm³)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12} (-)	ν_{23} (-)
1.46e-6	124	10.5	4.2	4.2	0.3	0.3

Table 2. Reference cohesive properties used in LS-DYNA simulations.

K (kN/mm³)	G_{1c} (kN/mm)	G_{IIc} (kN/mm)	$\sigma_{I,max}$ (kN/mm²)	$\sigma_{II,max}$ (kN/mm²)	α (-)
100	3.5e-4	11.31e-4	0.3	0.6	1.0

Although LS-DYNA is mainly known for its explicit time integration, the implicit Newmark time integration scheme was used as this was found to be more stable. Following a parametric studies on a double cantilever beam the numerical damping parameter ρ_∞ was selected as 0.6 and the time step was 0.066 ms. The constant displacement rate of 0.0025 mm/ms was applied to the nodes at the top of the spar in order to load the T-joint in tension.

4. Parameter study

The influence of different design parameters on the strength of the CFRP T-joint was assessed. Starting from the reference model described above, the first optimization step was to assess the influence of material parameters on the performance of the joint. The two most relevant material parameters were thought to be the fracture toughness of the composite, which determines the resistance against delamination, and the stiffness of the filler material.

4.1. Fracture toughness of the composite

Starting from the reference material properties given in Tab. 2, the mode I and mode II fracture toughness were increased and decreased by 50% with respect to the reference value. All other parameters remained the same for this study. It was found that the mode II fracture toughness hardly had an effect on the strength of the joint. Decreasing the mode I fracture toughness, however, resulted in a strength reduction of 3.31%. Increasing the mode I fracture toughness resulted in a strength increase of 2.97%. For real joints this could be achieved by changing the resin system or by introducing a binder system into the composite. Fig. 3 shows the specific strength of the joint as a function of fracture toughness.

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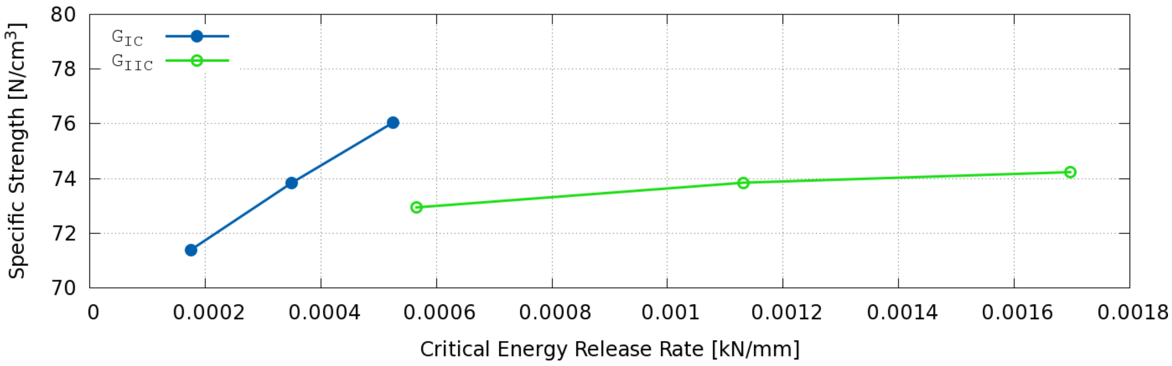

Figure 3. Specific strength as a function of fracture toughness.

4.2. Stiffness of the filler material

The filler material was found to be of great relevance for the strength of the T-joint. Initially, the filler was modeled as a transversely isotropic material with out-of-plane stiffness of 10.5 GPa. For the parameter study, the filler was replaced with isotropic materials of variable stiffness. In a first approach, an alternative softer material with a stiffness of 5.5 GPa and then a stiffer one with a stiffness of 70 GPa, equivalent to the stiffness of aluminum, were chosen. It was observed that for the softer material, the strength increased by 4.06 % and for the stiffer one, decreased by 4.42 %. With this information other low stiffness filler materials were considered: PTFE with a stiffness of 0.5 GPa and polystyrene with a stiffness of 3 GPa. The maximum joint stiffness was predicted for the polystyrene filler (increase of 5.17%). A further reduction of stiffness (PTFE) resulted in a reduction of overall strength. Fig. 4. Shows the predicted force-displacement curves for different filler materials.

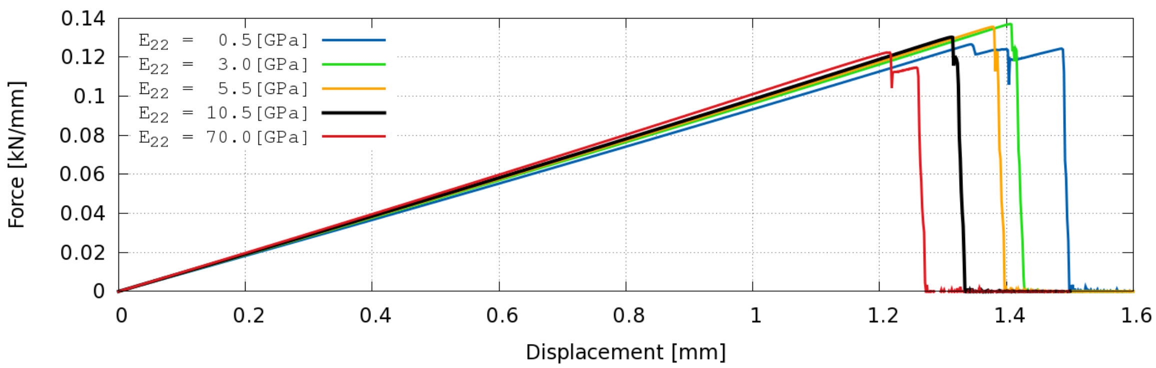

Figure 4. Predicted force-displacement curves for different filler materials.

Following the assessment of material parameters, the geometry of the joint was varied. On the one hand, the overlap of the flange and the skin were varied, on the other hand the curvature of the connection seen in Fig. 2. was changed.

4.3. Overlap length

For the reference joint [4,5], the overlap was 31 mm. For this parameter study simulations for the overlap length of 31 mm were compared against simulations for overlap lengths of 10 mm, 16 mm, 23

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mm and 46 mm. Interestingly an increase of strength was found for an overlap length of 23 mm whilst a reduction of strength was found for all other overlap lengths as shown in Fig. 5. It was also noticed that the delamination occurred between the filler and the skin for the two shortest spar flanges, whereas for the rest of the models, the delamination started between the spar and the filler and propagated through the overlap towards the end of the spar flanges. The delamination along the center line of the spar was found to be minimal for all variations of the joint, with only 1 to 3 cohesive elements failing.

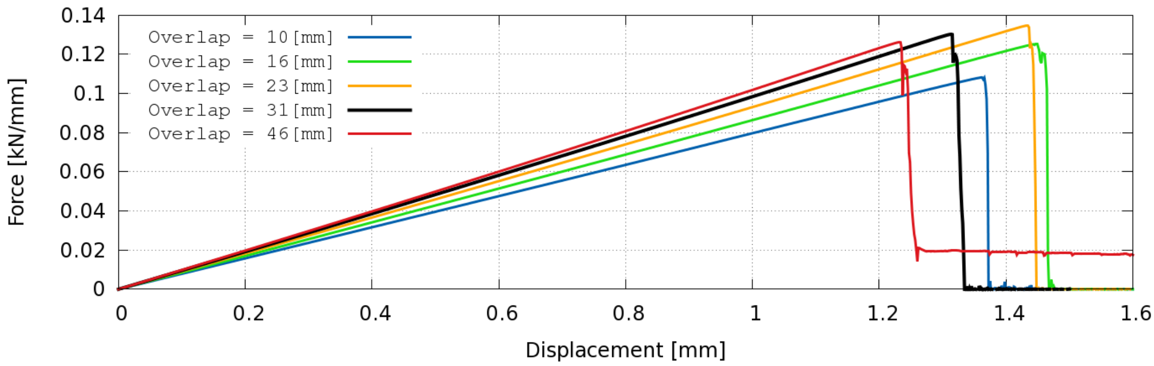

Figure 5. Predicted force-displacement curves for different overlap lengths.

4.4. Curvature

For the reference joint [4,5], the radius was 6 mm. For this parameter study simulations for a radius of 6 mm were compared against simulations for radii of 3 mm, 4 mm, 8 mm and 10 mm. As expected from an engineering point of view, a larger curvature leads to a reduction of stress concentration in the radius and therefore to an increase of strength. The predicted increase of strength for a radius of 10 mm is more than 50% as shown in Fig. 6.

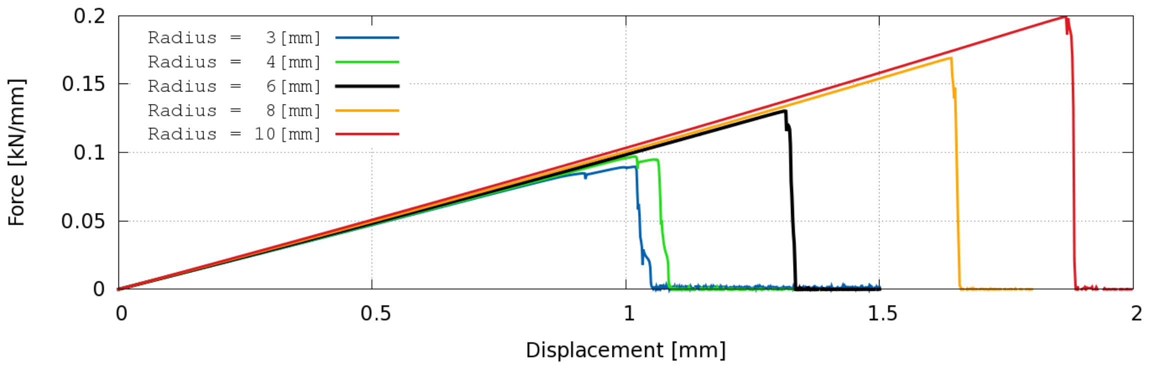

Figure 6. Predicted force-displacement curves for different curvatures.

Increasing the radius implies increasing the volume of composite material in the core and in general the mass of the structure. For that reason, the specific strength as a function of the radius was obtained and is shown in Fig.7. As it can be seen, it is also an ever-increasing function, which means no optimum was found.

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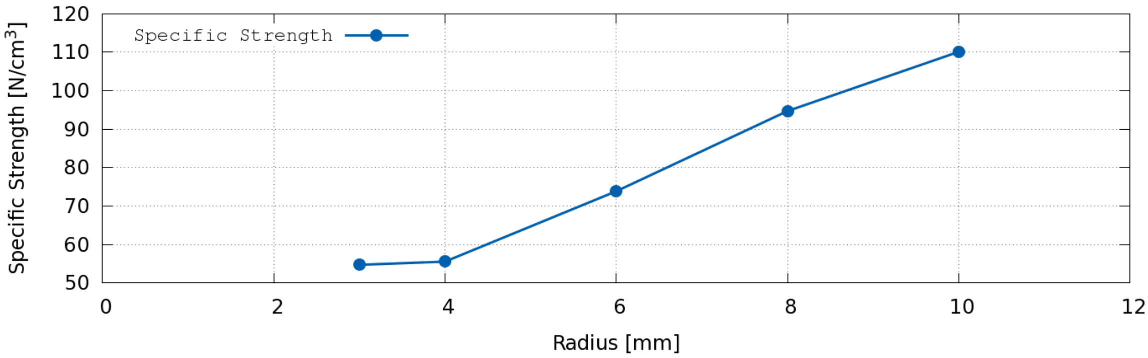

Figure 7. Predicted specific strength as a function of radius.

5. Discussion and Conclusions

Several material parameters and mechanical parameters were studied in the framework of this article. Whilst some of the results were clearly expected (e.g. an increase of strength with increasing mode I fracture toughness or an increase of strength with an increasing curvature), some of the findings were – at a first glance – counter intuitive. The numerical simulations found a strength optimum for an overlap length of 23 mm. Decreasing and increasing the overlap length from that value resulted in a reduction of strength. At first, one would expect an increase of strength with increasing overlap length. However, a longer overlap length results in an increase of bending stiffness. Higher bending stiffness may cause premature failure of the composite joint. Therefore the maximum strength is a result of a tradeoff between the sheer amount of material connected to each other and the bending stiffness. Keeping this in mind the fact that low stiffness fillers result in an increase of strength can also be explained as the local reduction of bending stiffness is – within limits – beneficial for the joint performance.
With all the information at hand, Heimbs et al. [7] manufactured several different types of T-joints incorporating some of the findings of [4] as well as findings from the numerical study described in this article. First of all, the resin system was changed from RTM6 to Cyctem Prism® EP2400 in order to increase the fracture toughness. In one configuration, analogous to [4,5] metallic pins were inserted in order to enhance the post-failure behavior of the joint. For the same configuration, a PEI filler was introduced instead of the braided composite filler. Here it was experimentally shown, that the peak load increased significantly compared to the baseline design with a braided CFRP filler. In another configuration, the potential of thermoplastic binders to increase the mode I fracture toughness was assessed. Heimbs et al [7] reported an increase of strength if thermoplastic binders are used.
The numerical parameter study has therefore been verified experimentally. Further details can be found in [7].

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