Numerical Analysis of Two Types Polymeric Fibre Composite Materials with Different Reinforcement Architecture for Creation of Innovative Snap-fit Joints

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Abstract. In this study we analyzed application of two types reinforcements of the polymer matrix composites (PMC): (1) fabric prepreg, (2) unidirectional prepreg and their hybrids for production of modern snap-fit joints. The numerical calculations were made in Abaqus program. Moreover, different layer systems and geometries were proposed to get the most effective joints. For each kind of joints the opening forces were assessed and Tsai-Hill strength criterion for estimation of a damage parameter inside of the PMC was applied. The proposed methodology leads to designing of more optimal joints for various engineering structures.

1. Introduction
Snap-fit joints were used for many years in various fields of technology starting from everyday objects (e.g. battery cover of remote control unit) and ending with joints in building constructions [2]. Despite this, they have not been subjected to scientific research so far, in contrast to conventional joints: rivets, adhesive, whose disadvantage is the presence of a significant number of parameters affecting their strength [10, 12, 14, 15]. The first study on the construction and design of snap-fit joints is P. R. Bonenberger’s textbook, but it only concerns components made of plastic. Despite the simplicity of their construction (the joint consist of only two pieces), they often have advantage shapes and can be manufactured not only from plastics but also from metals and fiber composites. The problem, which occurs during their manufacturing is the dimensional tolerance, which is difficult to achieve, e.g. due to plastic shrinkage. This causes appearance of excessive interference or clearance. In both cases, the joint will be poor quality. This issue was analyzed by the authors at work [3] and they proposed an optimized shape in which the joint has a constant force during its closing and opening.

In many cases, the snap-fit joints are inseparable, because they are situated inside the structure. Therefore, the current works are also focused on the use of shape memory materials [4, 6-7] for joint of beams. After heating the entire structure to appropriate temperature, the beams bend and thus two parts can be disconnected.

From the point of view of closing process it is necessary to consider a force and tactile feedback (FTF) which is important problem [5]. The force feedback refers to the force that must be overcome to close the joint, whereas the tactile feedback refers to vibrations that arise with an energy release during closing. Currently, joined parts are also manufactured using a 3D printing technology, what can
increase popularity of the snap-fit joints. However, during printing, it is necessary to comply with the relevant rules [8].

The other material used for manufacturing of the snap-fit joints are aluminum alloys used in aviation [11, 13]. To prepare the proper shapes of the joints an incremental methods and a loss methods can also be applied. However up to now there is no laboratory tests in this area.

The other innovative materials used for manufacturing of the snap-fit joints are different types of polymer matrix composites (PMC) obtained for example with application of prepregs and cured in an autoclave. In this area, there are also no reports in the literature. Therefore, in this paper we presented results of numerical simulations for joints:

- made of different types materials and different reinforcement architecture (layer systems),
- having 3 shape geometries: a flat, a concave and a convex.

As a result of the simulations, the forces that needed to open the joints in stretching or shearing processes were determined. The obtained simulation results can be useful for designers of the snap-fit joints.

2. Analyzed models

The snap-fit joints are composed of two parts. Most often they have a beam shapes with a gripping section, which is fixed in a socket [2]. To modeling of the snap-fit joints behavior one can apply also a cantilever beam. The closing force of the joint depends on the beam stiffness and in order to guarantee uniform stress distribution in the cross section it is necessary to introduce variable rigidity.

This study focused on modeling of the gripping section, which is usually a flat surface, figure 1a. Depending on the desired value of the opening force, the beam’s surface can be inclined to appropriate angle in relation to the socket. However, up to now, there is no solutions for including curvature in the gripping section of the snap-fit joint. Therefore, in this studies we analyzed 3 different shapes of the gripping part (figure 1): the flat, the convex and the concave.

![Figure 1. Analyzed geometries of the snap-fit models with the: a) flat, b) convex and c) concave shapes](image)

Dimension “a” in all models was equal to 20 mm. In our models we used 3 values of radius “R” – 75 mm, 62.5 mm, 50 mm for creation of the concave and convex models.

3. Numerical model

Numerical tests were made in the Abaqus program. Totally of 17 simulations were carried out:
- 5 for the model with the flat gripping part (for tension),
- 6 for the model with the convex gripping part (3 for tensile and 3 for shearing tests),
- 6 for the model with the concave gripping part (3 for tensile and 3 for shearing tests).
Tensile and shearing tests were modeled as incremental deformation process in direction of displacement $u_1$ or $u_2$ applied to the upper edge of the snap-fit joints as shown in figure 2.

Due to the fact that both parts have a relatively small thickness, shell elements were used in an amount: 4960 S4R for the socket and 3200 S4R for the beam with a gripping part.

In simulations, the socket was treated as an infinitely rigid element which was realized by removing all degrees of freedom. Two types of reinforcing materials in the PMC were used:

- a fabric - Gurit prepreg EP121-C20-45 - 0.23 mm thickness of the single elementary layer,
- unidirectional fibers - Gurit prepreg EP137-CR527_100-35 - 0.1mm thickness of the single elementary layer.

Five different layer configuration (systems) were considered for joints with the flat gripping part:

1. system - 2xEP121 0° - this is a reference PMC model,
2. system - EP137 0° / EP121 0° / EP137 0°,
3. system - EP137 0° / 2xEP137 90° / EP137 0°,
4. system - EP121 0° / EP137 0° / EP121 0°,
5. system - EP137 0° / EP137 45° / EP137 -45° / EP137 0°.

$0^\circ$ direction refers to a direction along the y axis. In simulations used general contact with friction coefficient equal to 0.1 between contacting surfaces of the socked and beam parts.

4. Numerical results of the analysis
The numerical analysis was divided into 3 stages:

(1) in the first stage, the snap-fit joint with the flat gripping part was analyzed with different arrangement of the composite layers. The joint was subjected to uniaxial tensile deformation until the force dropped completely. The reference model (model 1) had a 2xEP121 0° layer system. The EP121 material is made of a twill fabric and has the Young’s modulus equal to 55 GPa, i.e. smaller value than in case of aluminum. In the system 2, to make the joint more rigid, two layers of unidirectional fibers (Young’s modulus 148 GPa) were used in place of one layer twill fabric. The stiffness increased by about 50% and the weight decreased by about 11,5%. On the other hand, the stiffer joint causes an increase of stresses and for system 2 the permissible limit resulting from the Tsai-Hill criterion has been exceeded.

Figure 3. Force-displacement diagrams for the snap-fit joints with the flat gripping part
Figure 4. Tsai-Hill criterion (model 1)
A summary of the results for all systems is shown in figure 3. The fields for the Tsai-Hill criterion and thus the level of material effort are shown, for the system 1 in figure 4. In table 1, all results for 5 analyzed layer systems were collected.

|                | 1 (ref) system | 2 system | 3 system | 4 system | 5 system |
|----------------|----------------|----------|----------|----------|----------|
| max Tsai-Hill  | 0,65           | 1,1      | 0,78     | 0,78     | 0,79     |
| max force [N]  | 15,7           | 31,3     | 24,9     | 28,1     | 25,1     |
| mass [g]       | 1,48           | 1,31     | 1,14     | 1,77     | 1,14     |

(2) in the second stage of the numerical studies, tensile deformation tests were performed for the concave and the convex joints. It should be emphasized, that the reference layer system for the convex and the concave model are shown in figure 5 and figure 6 respectively. However, in the both cases there is no clear effect of geometry change on the value of the maximum force.

(3) the third stage of the numerical investigations the concave and convex joints were subjected to shear deformation tests along the axis “z”. The joint with flat gripping part was not tested, because in this case the movement along the “z” axis is not limited, i.e. the force force is equal to zero. For the convex and the concave joints, we noticed change of the shear force when the radius “R” changes from 75 mm to 50 mm (figure 6 and 7). The maximum shear force is an order of magnitude smaller in comparison to the maximum tensile force. However, in many cases such strength reserve may be sufficient to protect the joint from slipping of the one parts.

Testing of the snap-fit joints in various load states is also justified if we consider connectors application simplifying the real shape of the joints. For large structural assemblies with complex
shapes and connected by system of snap-fit joints, it is not possible precise modeling of this structural element due to complicated geometrical shape. But knowing the characteristics of the single joint it is possible to reduce this system of snap-fit joints to the new one simplified by application set of connectors.

5. Conclusions
The paper provides information about influence of different reinforcement architecture of the PMC and geometric shapes on the strength of the snap-fit joints. As distinguished from plastic and metals the PMC provide significantly wider design possibilities. From the simulations carried out the following conclusions can be formulated for models with flat gripping part:

- replacement on one fabric layer (model 1) into two layers of unidirectional fibers (model 2) doubles the opening force,
- except for model 2, the material effort estimated by the Tsai-Hill hypothesis not exceeded limiting value and was in the range of 0.65 – 0.79.

In case of the tensile deformation tests, the shape change of the gripping part does not influence substantially the carrying force. However, if the joint would work in a complex load state, e.g. shear state due to twisting of the whole structure, the following conclusions were drawn:

- it is better to use models with the convex gripping part. Then the increase of the joint opening force is about 45% higher with respect to the concave models,
- the radius “R” (figure 1b and 1c) have a substantial influence on the shear joint strength. The radius change from 75 mm to 50 mm results in increase of the joint strength by about 67% for the concave models and about 50% for the convex models.

The numerical model can be extended to include damage or cracking process, as it was done for other composite materials, e.g. [16 – 26].

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