Numerical Investigation of the Forming Behavior of Polymer Composite-Metal Hybrids using Fiber Reinforced Thermoplastic Tapes with Discontinuous Layup

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1 Introduction

The automotive industry is facing stronger requirements for crash safety and environmental friendliness of passenger cars from legislators, society and customers. This is reflected in legal requirements that regulate CO_2 fleet emissions over the next few years as well as the relevance of CO_2 emissions and vehicle safety as purchase criteria for vehicles [1, 2]. Fiber-reinforced plastics (FRP) offer a great potential to meet these requirements due to their high specific strength and stiffness as well as energy absorption capacity [3]. In particular, fiber-reinforced thermoplastics (FRTP) are suitable for large-scale production owing to their good recyclability and short cycle times [4]. Continuous fiber reinforced thermoplastic composites such as organo sheets or laminates are processed in a thermoforming process to produce shell-shaped structural components. However, these semi-finished products have high material costs. In order to overcome the higher cost of FRTPs, the manufacturing of polymer composite-metal hybrid structures in a hybrid lightweight design is now currently being considered in the industry. This also offers the advantage of joining hybrid structures to the metallic body-in-white using joining operations already established in the automotive industry, e.g. welding [5]. According to the current state of the art, hybrid components are manufactured in sequential processes. An example of this is the A-pillar of the Porsche 911. Both the FRTP and the steel sheet are formed separately. Then, in a third processing step, both components are joined to form a hybrid structure [6]. To improve efficiency, hybrid components consisting of FRTP and sheet steel can be produced in a one-step forming process. However, FRTPs have limited formability compared to steel sheets. This is primarily due to the lack of plasticity of the fibers as well as to the limited shearing of the weft and warp threads in fiber fabrics, which can lead to fiber displacement, fiber breakage or wrinkling for complex-shaped components [7].
The improvement of the formability of FRPs has been an intensive area of research for years. Several approaches have been developed to achieve global ductility of FRPs. The first approach, which has been further developed over several years, is the fiber alignment process to produce fiber mats of short fibers. For this purpose, short fibers are sprayed onto a surface via a nozzle using glycerine as a carrier fluid to align the rovings. The carrier fluid is then pumped off or evaporated [8, 9]. Another approach to create a globally ductile material behavior of FRP is to cut the fibers in dry or impregnated continuous fiber semi-finished products (e.g. fabrics or organo sheets) into lengths between 25 and 150 mm [10, 11, 12]. The separation of fibers from conventional prepreg semi-finished products can also be done by a laser. In this process, the semi-finished product is micro-perforated [13, 14].
In another method, recycled carbon fibers are processed into a drapable organo sheet. For this purpose, carbon roving shreds are spun into a yarn and wrapped with a PA6 filament for stabilization. The average fiber length is 25 mm. During the forming process, the carbon roving shreds can slide within the spun yarn, so that improved formability can be achieved [15, 16].
In this paper, a new approach to improve the formability of FRTP laminates using discontinuous tape sections is presented and used in a simulation model for a one-step forming process of a hybrid intrusion beam. In this process, the forming of the steel sheet and FRTP as well as the joining process of both semi-finished products takes place in a single forming step. The process chain of the sequential as well as the one-step forming processes for manufacturing hybrid shell-shaped components are shown in Figure 1. To show the potential of the improved formability of the new approach, the simulation results are compared with those of a forming simulation using conventional FRTP laminates consisting of continuous tapes.

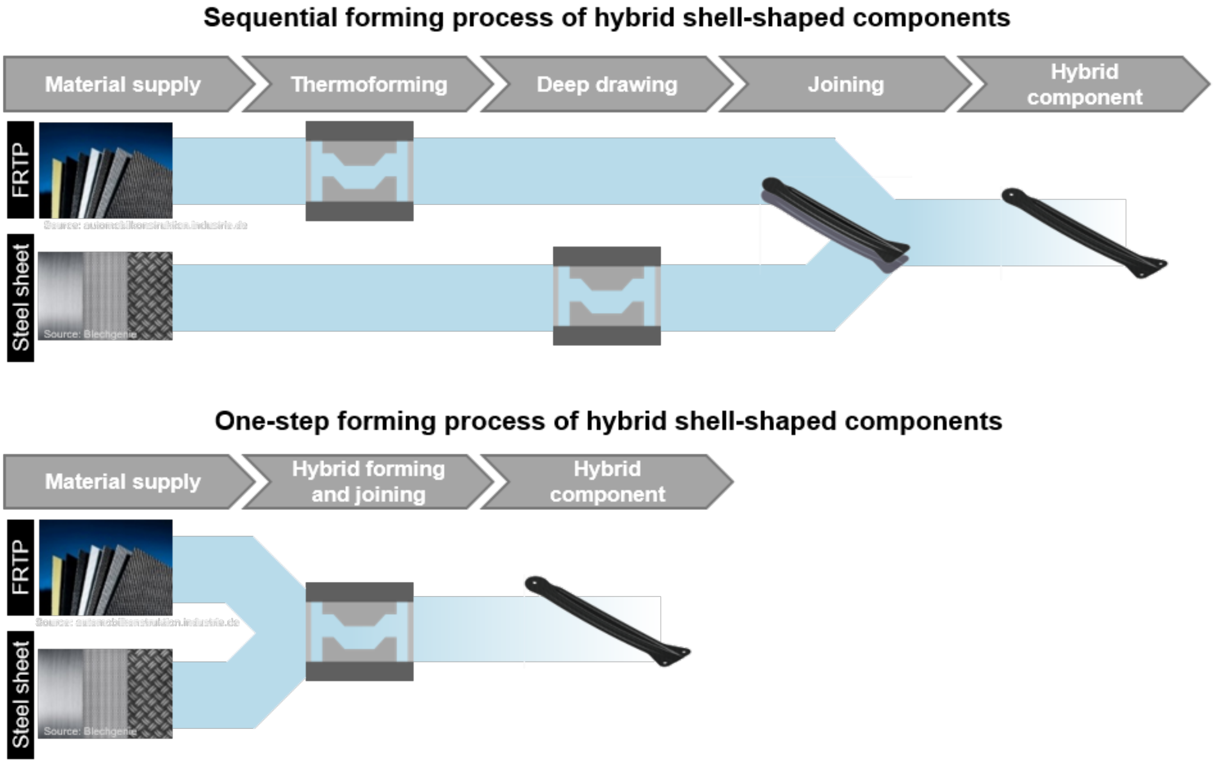

Fig.1: Comparison of the sequential and one-step forming process for the production of hybrid shell-shaped components.

2 Concept of the FRTP laminates using discontinuous tape sections

From the approaches presented in the introduction, it can be seen that the fibers are the limiting factor to achieve high deformations during forming. Improved formability is thus mainly achieved by shortening the fibers and by allowing these shortened fibers to move relative to each other during forming. The novel approach presented in this paper also applies this principle. However, the global ductility of the laminate is produced using a modified tape laying process and conventional thermoplastic tape reels. As opposed to the conventional tape laying process, in the adapted tape laying process a tape strip does not consist of one continuous tape, but of several discontinuous tape sections deposited end to end. The design of the global ductile FRTP laminate is shown in Figure 2 and compared to a conventional laminate. In the adapted tape laying process, the tapes are laid from the reel and cut to the required length L_T to form tape sections. Between each discontinuous tape sections, small gaps are left. These separation gaps allow the tape sections to slide relative to each other during the forming process to create a globally ductile material behavior. The tape sections of the adjacent tape strips in-plane are laid down with an offset. This results in an offset O_{IP} between the separating gaps of the adjacent tape strips. Optionally, the out-of-plane layers can also be offset by O_{OP} transverse to the fiber orientation. The offsets O_{IP} and O_{OP} are used to enable a flow of force between the tape sections and to fill any holes or grooves that occur during the sliding process.
The concept of discontinuous tape sections presented above offers the possibility of adapting the configuration of the laminates locally within a layer or across the entire laminate thickness according to the geometry of the component and resulting stresses developing during the forming process. This enables the development and manufacturing of a customized semi-finished product that meet individual requirements, e.g. formability and mechanical properties. Furthermore, the semi-finished product can consist of both discontinuous and continuous tapes. In areas where high deformations are required, discontinuous tape sections are used, whereas in areas of low deformation, conventional tapes can be applied. Furthermore, the tape laying process offers a high reproducibility of the quality of the semi-finished product. This includes, for example, a low deviation in fiber orientation.

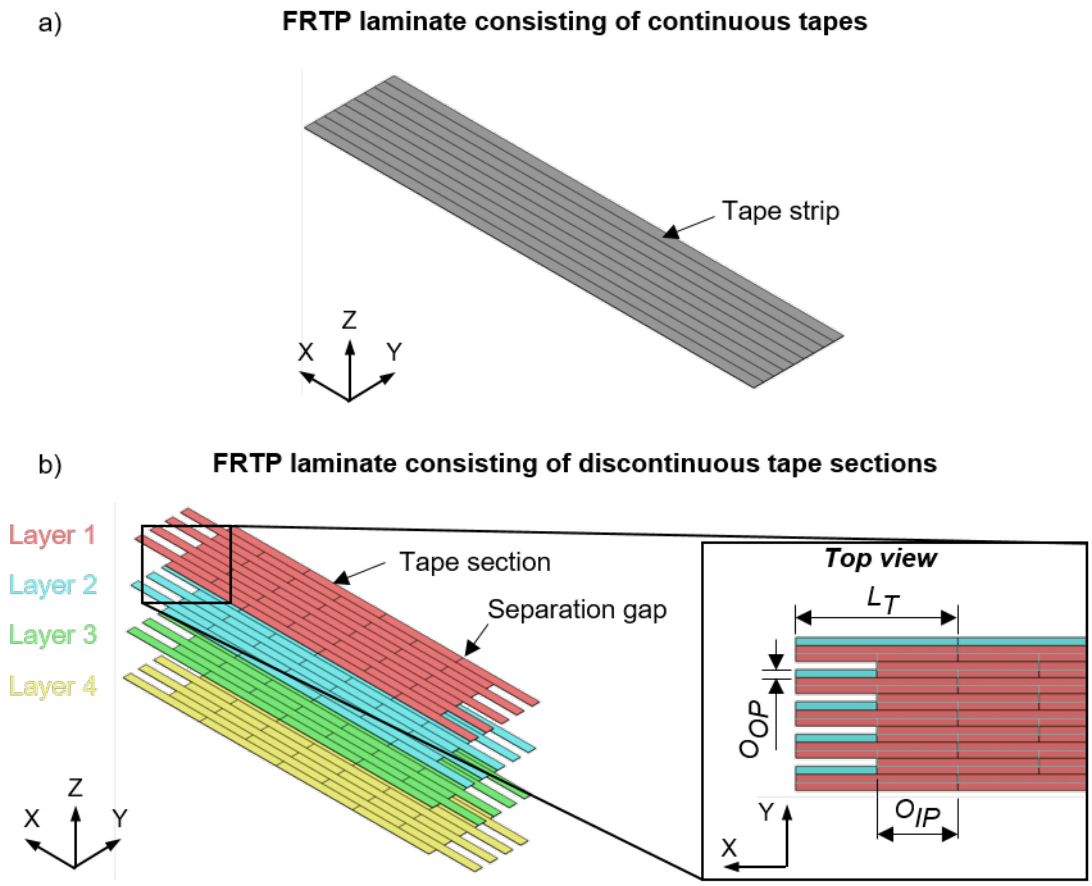

Fig.2: Comparison of the structure of an FRTP laminate with a) continuous tapes and b) discontinuous tape sections.

3 Numerical modeling of the one-step forming process

For the simulation of the one-step forming process of an intrusion beam, two models are developed using LS-Dyna which differ in the structure of the FRTP laminate. In the first model, the FRTP laminate is modelled using continuous tapes. The second model consists of discontinuous tape sections. For this model, two different laminate configurations are considered. The structure of the model is shown in Figure 3.

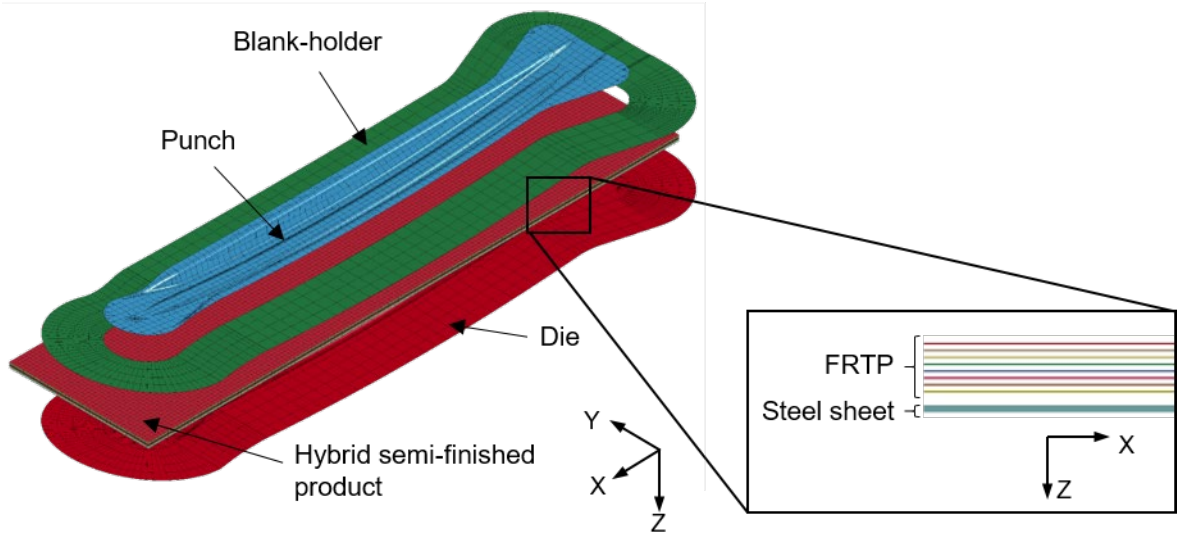

Fig.3: Structure of the simulation model.

3.1 Forming tool

The steel-based tool used to model forming of the hybrid semi-finished product consists of a die, punch and blank holder. All components of the tool are modelled as shell elements with a rigid behavior (**`*MAT_RIGID*`**). Previous numerical investigations showed that forming without a blank holder leads to wrinkling. Due to this, the forming is performed with a blank holder, which introduces a blank holder force of 30 kN.

3.2 Hybrid semi-finished product

The hybrid semi-finished product consists of a 1 mm thick steel sheet and a 2 mm thick FRTP laminate. The steel sheet is placed on the side facing the die. The FRTP is stacked on top of the steel sheet.

3.2.1 Steel sheet

For the steel sheet, the grade DC01 (1.0330) is used and modelled using the material model **`*MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC_NLP_FAILURE*`**. This material model is suitable for the simulation of metallic forming processes and enables the use of form-limit diagrams in addition to stress-strain curves. The material data were applied based on the material characterization of Vasile et al. [17].

3.2.2 FRTP laminate

For the continuous and discontinuous tape laminate configurations, the studied FRTP laminate consists of 8 layers of thermoplastic UD tape. Each layer has a thickness of 0.25 mm. A symmetrical $[90/0/90/0]_s$ ply structure is modelled for the laminates. In these laminates, 0° corresponds to a fiber orientation along the X-axis. In the laminate using continuous tapes, each layer consists of one part. In the second model using discontinuous tapes, each tape section was not modelled as an independent part. An efficient approach was rather developed in which a single layer consists of only four sub-parts. These sub-parts contain several tape sections that are not in direct contact with each other. Nevertheless, the tape sections interact independently of each other. This approach is shown in Figure 4. For the laminate, the tape material from Celanese (Celstran® CFR-TP PA6 GF60-01) is used, which is composed of a PA6 matrix and glass fiber with a fiber volume content of 39%. The material model **`*MAT_REINFORCED_THERMOPLASTIC*`** is used to model the FRTP. For this purpose, comprehensive material characterizations were carried out, including tensile tests parallel and transversal to the fiber direction according to DIN EN ISO 527-5 as well as shear tests according to DIN EN ISO 14129. These tests are carried out above the melting temperature of the material at about 230 °C.

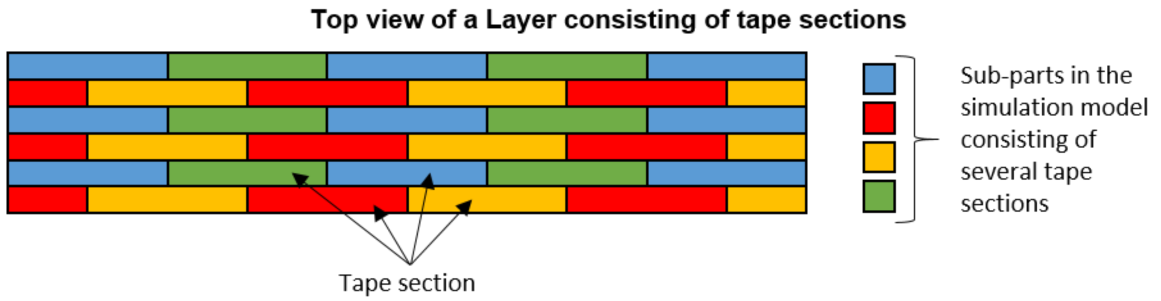

Fig.4: A layer of FRTP laminate using discontinuous tape sections. The layer composed of four sub-parts consisting of several tape sections that are not in direct contact.

3.3 Boundary conditions and contact

During forming processes of FRTP laminates, interlaminar sliding processes play a decisive role. This effect is of particular relevance for laminates with discontinuous tape sections in order to be able to model the sliding processes during forming. The sliding behavior depends in particular on the relative velocity v, der viscosity η of the matrix material and the surface pressure σ_N. The Stribeck curve is usually used to describe the interlaminar sliding processes. This curve describes the coefficient of friction as a function of the Hersey number *He*. The three influencing parameters mentioned above are included in the Hersey number

$$He=\frac{\eta \cdot v}{\sigma_N}. \quad (1)$$

Using the contact card ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_COMPOSITE***, the parameter-dependent friction can be modelled as a function of the Hersey number and is used to describe the contact between the single layers. The FRTP as well as the steel sheet is joined together in the forming process by a PA6 based adhesive film. Due to this, this contact card is also applied for the contact between FRTP and steel sheet. Nishi et al. conducted experimental tests to describe the friction as a function of the Hersey number for a forming simulation of FRTP [18]. This data base is used for the model described in this paper. For the forming simulation, an isothermal condition of 230 °C is assumed. Simplified, a constant friction of 0.3 is used for the contact between the semi-finished product and the tool and modelled via the contact card ***CONTACT_FORMING_SURFACE_TO_SURFACE_MORTAR***.

4 Results

In the first step, the results of the simulation model for the FRTP based on continuous tapes are presented. Based on the stress distribution in the intrusion beam induced by the forming process, the layer structure for the second simulation model using discontinuous tapes is then derived. The evaluation examines the stress distribution in the FRTP and the forming limit in the steel sheet.

4.1 One-step forming process using continuous tapes

Using the forming limit curve (FLC), the true strains of the steel sheet are first considered. Figure 5 a) shows the FLC as well as the major and minor strains of all elements of the steel sheet. The strains of the elements are significantly below the forming limit curve. Cracks or strong thinning of the sheet are not to be expected. Figure 5 b) shows the formed steel sheet. The contour of the intrusion beam in the semi-finished product is highlighted. The ratio between the strain of the elements and the corresponding value of the forming limit curve is shown. Element strains above the FLC are recorded if this quotient is greater than 1. The maximum value of 0.28 is located in the head area of the intrusion beam (see red area in Figure 5 b)). DC01 is a deep drawing steel with a high plasticity. As a result, complex shaped components with high degrees of forming can be realized with this steel grade.

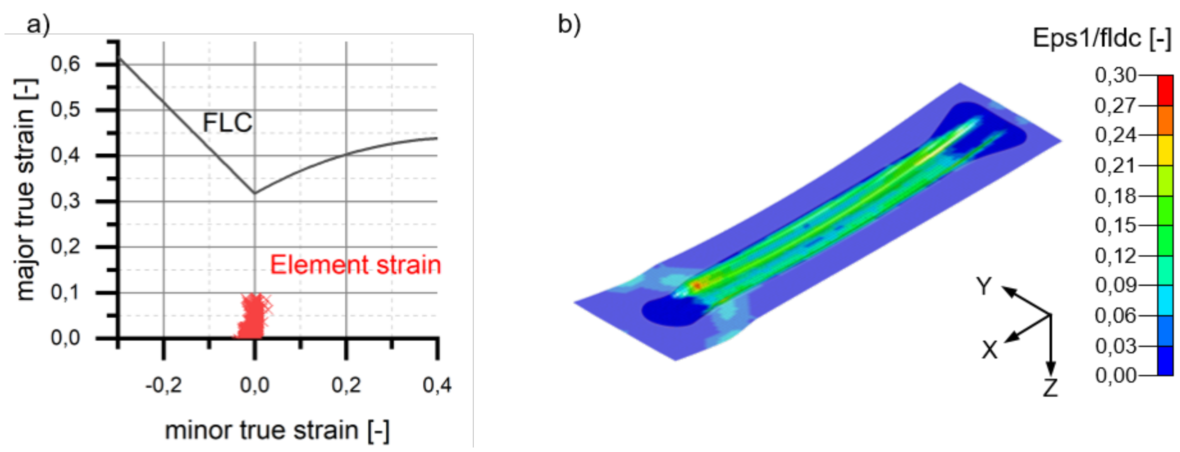

Fig.5: a) Main and secondary strain of the elements of the steel sheet as well as the forming limit curve; b) Strains in the formed steel sheet.

Figure 6 shows the stress distribution of the FRTP layers with 0° and 90° fiber orientations. In the FRTP layers, which have a fiber orientation of 0°, no excessive stresses can be detected (see Figure 6 a)). The maximum tensile strength in the fiber direction is 455 MPa at a temperature of 230 °C according to the material characterization. In the X-Z plane, along the whole length the intrusion beam has a large constant radius in relation to the drawing depth. Accordingly, no abrupt changes in geometry (e.g. height

jumps) can be detected. Due to this, the degrees of forming along the 0° fibers are low, which also affects the low stresses.
On the other hand, looking at the layers with a fiber orientation of 90° (see Figure 6 b)), significantly greater stresses can be observed. Stresses exceeding the tensile strength can be seen in the bottom and the radius between bottom and flank (see grey areas). The ratio between radius and drawing depth is clearly more pronounced in the Y-Z-plane than in the X-Z-plane. As a result, higher deformation is occurring along the 90° fibers due to the geometrical changes in the intrusion beam.
The first simulation model shows no critical strains or stresses exceeding the limits in the steel sheet nor in the FRTP layers with 0° fiber orientation. In the layers with a fiber orientation of 90°, the tensile strength of the fibers is exceeded in some spots. This can lead to fiber damage. To compensate for the high degrees of forming, the continuous tapes need to be replaced by discontinuous tape sections in the 90° layers.

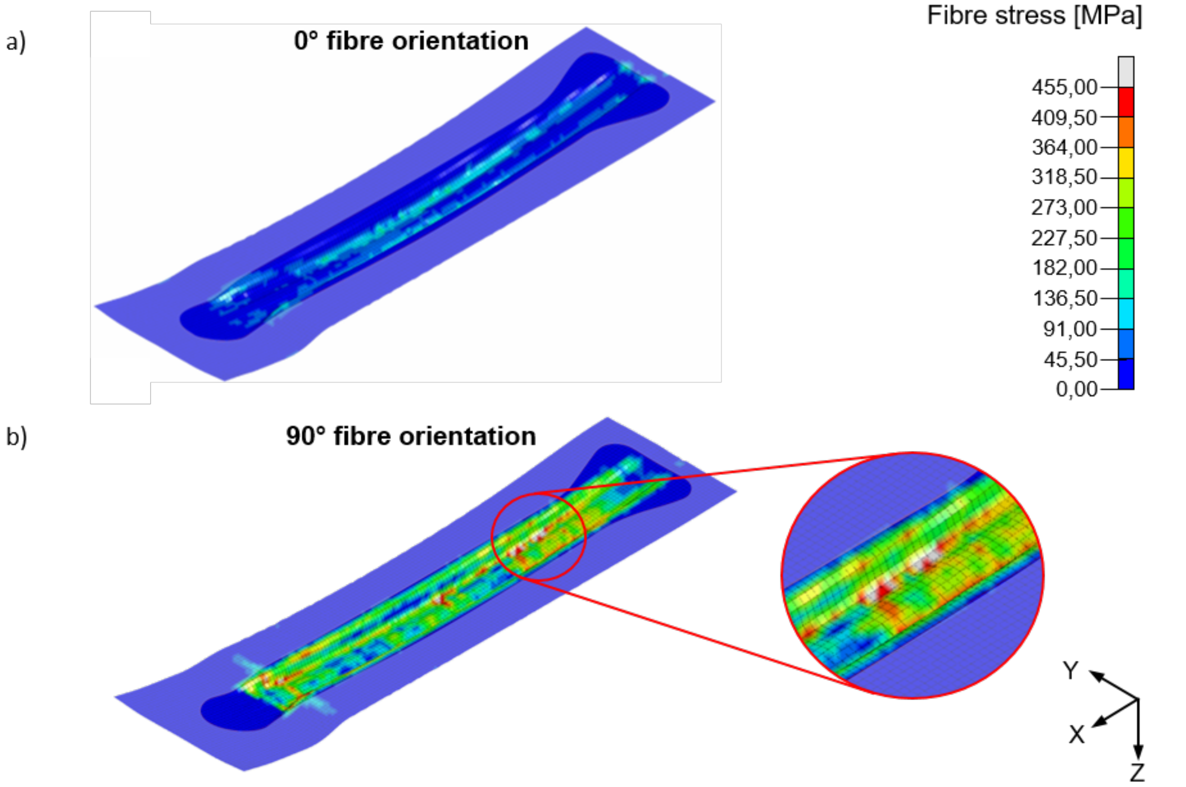

Fig.6: Stress distribution of the fibres considering a) the layers with 0° fibre orientation and b) with 90° fibre orientation.

4.2 One-step forming process using discontinuous tape sections

Due to the fiber tensile strength being exceeded in the bottom area of the 90° layers, discontinuous tape sections are used. Therefore, the gaps between successive tape strips are positioned in a way that they are located in the bottom area of the intrusion beam after forming. Sliding processes are intended to reduce the high stresses in this area. The tape sections are positioned "quasi-symmetrically" along the X-Z axis and have a tape section length L_T of 90 mm starting from the center axis of the semi-finished product. Thus, the tape section length is significantly greater than the drawing depth. At the edges of the semi-finished product, the tape sections have a length of 25 mm and 45 mm respectively. The in-plane overlap O_{IP} is 20 mm. An out-of-plane overlap O_{OP} of 0 mm is considered. The structure of the layer using discontinuous tape sections is shown in Figure 7 a).

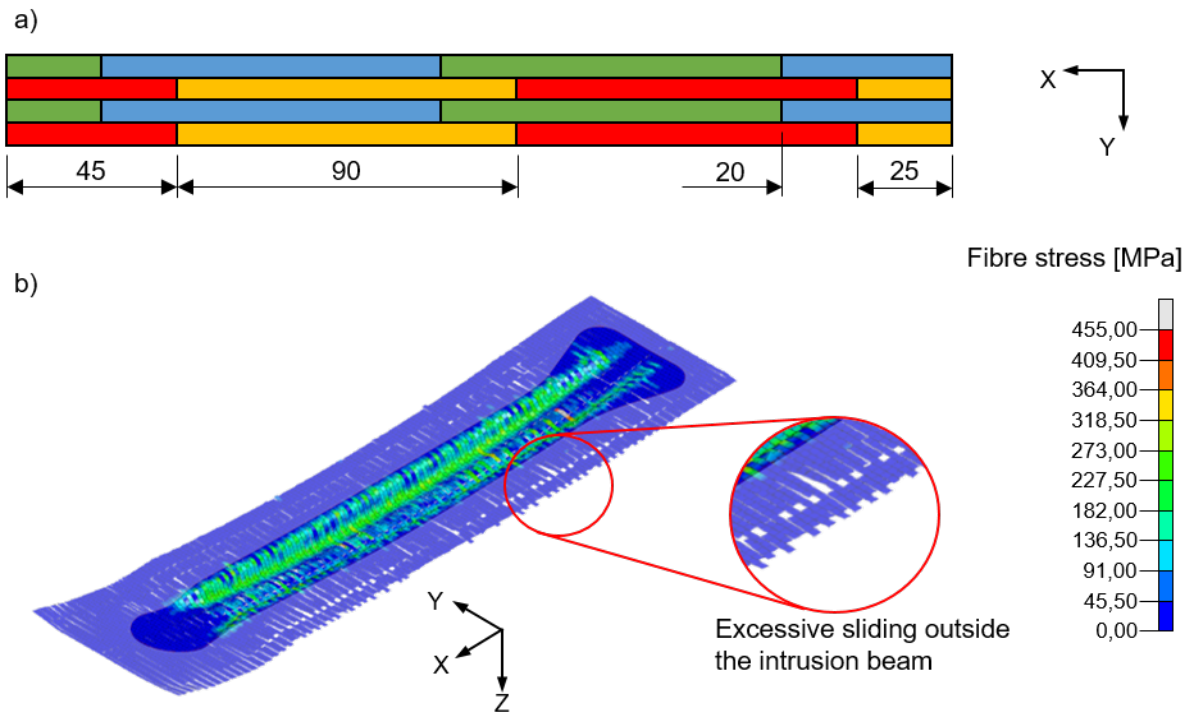

Fig.7: a) Layer structure of the FRTP using discontinuous tape sections; b) Stress distribution of the layer, consisting of discontinuous tape sections.

The resulting stress distribution in the FRTP composite layers using the discontinuous tape model is discussed in this section.
In Figure 7 b), a significant compensation of the stresses induced from the forming process can be seen. The sliding of the tape sections results in a surface enlargement of the FRTP layer as in a ductile steel sheet. In addition, extensive sliding in the form of large holes can be seen at the edges of the semi-finished product in the short tape sections. In this area, high stresses were not observed during the forming simulation using continuous tapes. Therefore, sliding of the tape sections is not required in this area and does not lead to any improvement in reduction of excessive stresses.
For further investigation of laminates manufactured from discontinuous tapes, the tape section length is reduced from 90 mm to 40 mm. Thereby, additional separation gaps are created in the area of the flank in the intrusion beam. The tape sections at the edges of the semi-finished product are extended to 55 and 75 mm, respectively. The in-plane overlap remains constant at 20 mm. The new layer structure is presented in Figure 8 a).
It can be seen that a smaller tape section length can further reduce the stresses induced in the FRTP by the forming process (see Figure 8 b)). This reduction is mainly visible in the flank of the intrusion beam. The shorter tape section length results in additional fiber discontinuity that enhance sliding. To decrease the stresses in the forming process, short tape sections should therefore be selected as this results in greater degrees of freedom for the sliding process. However, for the mechanical properties of the component (e.g. strength, stiffness, energy absorption capacity) longer tape sections might be preferable. Therefore, the forming process and required mechanical structural properties of the component should specifically define the configuration of FRTP manufactured from discontinuous tape sections [19].
By extending the tape sections at the edges of the FRTP semi-finished product, it can be seen that large holes in the flange area are inside the intrusion beam are induced by the excessive sliding of the beam. In practice however, this has to be avoided as large holes lead to extensive thinning of the material providing crack initiation points and reduced mechanical properties. For that reason, these holes should be avoided or pushed outside the component area.

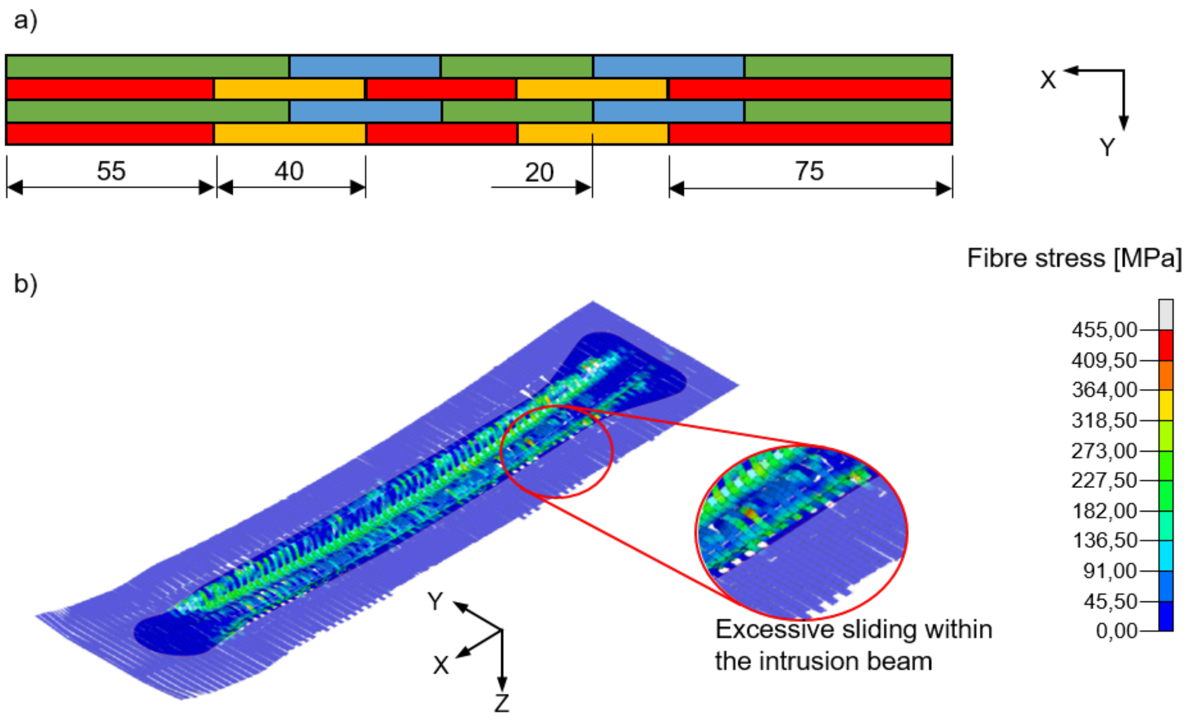

Fig.8: a) Revised structure of the FRTP using discontinuous tape sections; b) Stress distribution of the revised layer structure, consisting of discontinuous tape sections.

5 Conclusion

In this paper, a novel approach to improve the formability of FRTP laminates was presented, in which the layers are built up in a brick pattern like structure of discontinuous tape sections. For this purpose, a one-step forming process for an intrusion beam with FRTP consisting of continuous tapes and steel sheet was first modelled in LS-Dyna. In a second model, a FRTP consisting of discontinuous tape sections is modelled. Both models are compared on the basis of stress distribution after forming and formability.

It was found that very high stresses occur in the FRTP using continuous tapes. These high stresses appeared especially in the bottom area of the intrusion beam. By substituting the continuous tapes by discontinuous tape sections with a length of 90 mm, the stresses can be significantly reduced. Accordingly, the discontinuity in the FRTP semi-finished product were positioned such that they are located in the bottom area after forming. A further decrease of the tape section length to 40 mm showed additional reductions of the stresses. This is due to the increased number of fiber discontinuity, which allows for greater degrees of freedom in the sliding of the tape sections. Short tape sections should therefore be selected to reduce the stresses induced by the forming process. However, long tape sections are preferable when higher mechanical properties are targeted. As a results, the configuration of the FRTP semi-finished product consisting of discontinuous tape sections has to be adapted specifically to the forming process, component geometry as well as to the required mechanical properties.

To improve the prediction quality of the model as well as the understanding of the sliding behavior of the tape sections, the experimental development of a Stribeck curve for the specific tape material used is necessary. So far, a Stribeck curve of a comparable material has been used, which differ in the composition of the tape material and the fiber volume content. Furthermore, the model will be extended to include thermodynamic effects. This allows the temperature- or viscosity-dependent sliding of the tape sections to be analyzed even more precisely. In addition, experimental tests are carried out to investigate the influence of the configuration parameters (e.g. tape section length, overlap length, number and position of the separation gaps) on the mechanical properties and formability. With this knowledge gain, the configuration of the FRTP can be derived and optimized by a multi-criteria evaluation.

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7 Literature

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