STRESS ANALYSIS AND DESIGN SUGGESTIONS FOR MULTI-LOOP CARBON ROVING ROSETTES TO REINFORCE BOLT-LOADED OPEN-HOLE LAMINATES

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Abstract

The potential of mechanical joints in monolithic carbon fiber reinforced plastics (CFRP) laminates is limited by the poor local bearing response under bolt loads. To improve the mechanical performance of bolt-loaded open holes, often metallic inserts or fiber reinforcements like Advanced and Tailored Fiber Placement (AFP, TFP) are used. In this work, an alternative to AFP and TFP is investigated, where winded carbon rovings are twisted around the bolt and work without sewing. These multi-loop rovings consist of turns around the hole and free slings in the design area around the hole.

Based on previously conducted experimental and numerical studies, published in Botzkowski et al. 2016 [1], a model generator has been developed to build up three-dimensional finite element (FE) models on mesoscopic level. The model generator is capable of considering variable design parameters of the multi-loop rosette as well as manufacturing effects like changes in cross sections of the rovings. The applied material models have been parametrized by experimental tests at single-loops and non-reinforced reference laminates [1]. By applying the model generator, various multi-loop configurations with varying number of turns, number of loops, loop orientations and loop lengths are generated and evaluated in terms of their stress behavior and load bearing capacity. Finally, design proposals for winded multi-loop roving rosettes are derived.

1. Introduction

One of the main challenges of multi-material design with carbon fiber reinforced plastics (CFRP) is to find an appropriate joint method. Compared to adhesive bonded joints, mechanically fastened joints offer the advantage of easy repair and replacement of components. However, CFRP laminates with bolt-loaded open holes provide low local bearing capacity [2]. To improve the mechanical performance of bolted joints, often metallic inserts or fiber reinforcements like Advanced and Tailored Fiber Placement (AFP, TFP) [3, 4] are used. For an optimal application and reliable virtual design of TFP reinforcements, appropriate material models are needed and the real manufactured fiber path, including local manufacturing effects, needs to be considered [5, 6].

An alternative to AFP and TFP are winded carbon rovings, which are twisted around the bolt [1]. As illustrated in Fig. 1(a), the multi-loop rovings consist of turns around the hole and free slings in the design area around the hole. The roving rosettes are preformed, bindered and impregnated in advance, see Fig. 1(b). For final impregnation of the bolt-loaded laminate, the pre-impregnated rosettes are

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applied around the hole on both sides of the laminate as shown in Fig. 1(c). The winding technology provides a larger contact area to introduce bearing forces and omits a preceding stitching process, which is needed for TFP to fix the roving on the basis laminate. However, manufacturing effects like varying roving cross sections can also have large influence on the deformation and failure behaviour of winded carbon rovings.

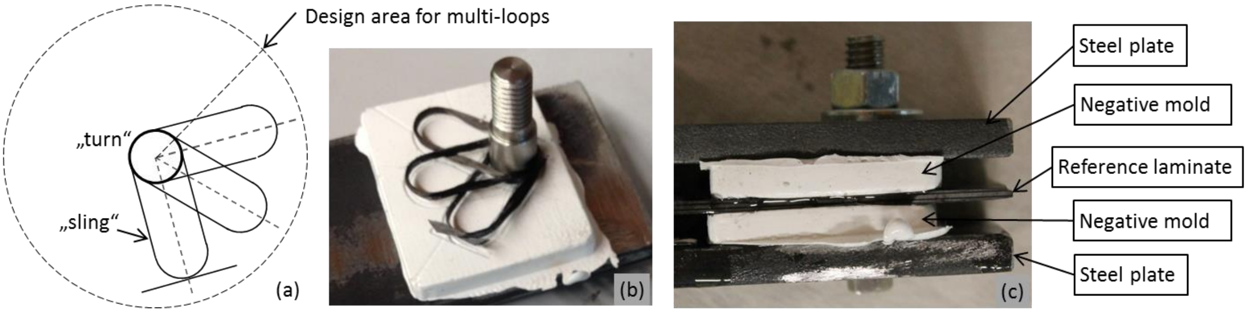

Figure 1. (a) Fiber path of an example multi-loop configuration, (b) preformed, bindered and impregnated multi-loop, inserted in negative mold and (c) manufacturing of the laminate with application of the impregnated loops on both sides of laminate, cf. [1].

In previous work of the authors [1], finite element (FE) models have been developed to describe the deformation and failure behavior of reinforced open-hole laminates. The material models have been parametrized by means of experimental tests at single-loops and non-reinforced reference laminates. The accuracy of the models was validated by experimental tests of an open-hole laminate reinforced by three loops. In the present work, a model generator is presented which utilizes the validated material models and builds three-dimensional FE models on mesoscopic level. The model generator is capable of considering variable design parameters of the geometry of the multi-loop rosette. The FE models also consider observed manufacturing effects, e.g. affected cross sections of the multi-turn rovings around the bolt. By applying the model generator, various multi-loop configurations with varying number of turns, number of loops, loop orientations and loop lengths can be generated and evaluated in terms of their stress behavior and load bearing capacity.

2. Single loop configurations used for FE model setup and validation

To build up suitable finite element models of open-hole laminates with winded reinforcements, firstly, single roving loops have been modelled and analyzed [1]. The modelling procedure of the single-loops is illustrated in Fig. 2. A Matlab-script converts the geometric data of the winded fiber path into a 3D-geometry, where the cross section of the roving can be modelled in a variable way, according to observed manufacturing effects. Based on the resulting 3D-geometry, a mesoscopic FE model is generated for Abaqus Explicit. The roving is modelled by SC8R shell elements with enhanced hourglass control and activated element deletion. The material orientation is generated by a Python-script along the edges of the elements. To model delamination between adjacent rovings, a separation layer is defined by incompatible mode elements C3D8I. For intra-laminar failure analysis, the Hashin initiation criterion [7] is applied in conjunction with the progressive damage model of Lapczyk [8]. The material models are parametrized and validated by means of experimental characterization tests, by comprehensive experience from previously conducted tests [9] and by experimental validation tests on different single-loop configurations [1].

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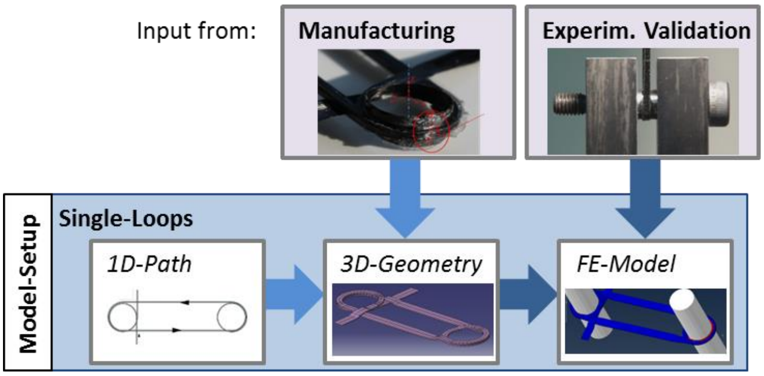

Figure 2. Workflow for FE model setup of single-loops, based on manufacturing data and experimental validation.

3. Open-hole laminate with multi-loop reinforcement

To assemble FE models of multi-loop laminates, the models for single-loops have been combined with a model of the reference-laminate. The modelling procedure for multi-loop laminates is illustrated in Fig. 3. The plies of the reference-laminate are represented by individual layers of SC8R shell elements and connected by cohesive zones to model delamination. The load bearing bolt is defined as rigid body, where a hard contact is defined between the bolt and the hole to transfer the loads.

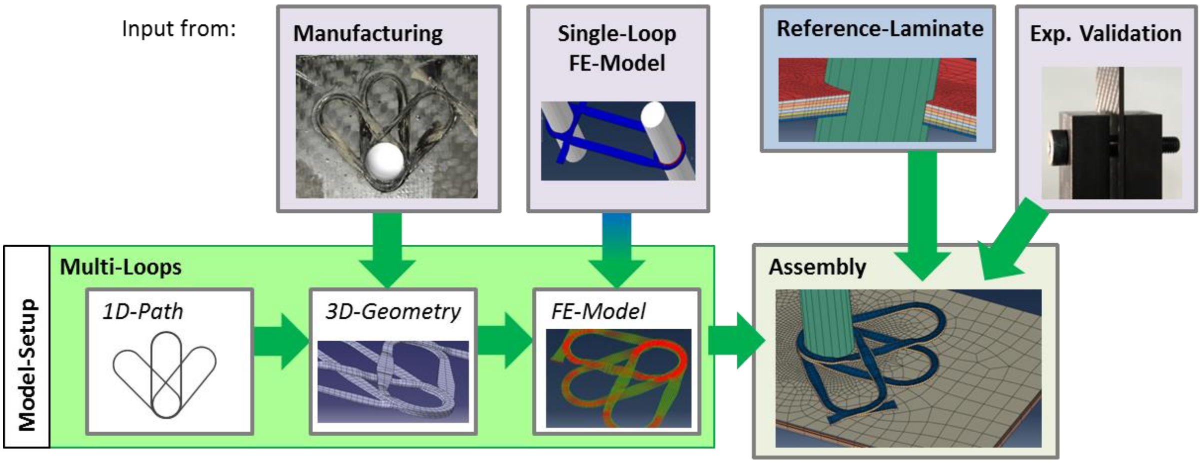

Figure 3. Workflow for FE model setup of multi-loop reinforced open-hole laminates, based on manufacturing data, single-loop FE model and experimental validation.

As above for the single-loops, model setup and material parameters of the reference-laminate have been determined by experimental tests on non-reinforced reference-laminates [1]. In addition, experimental tests on reinforced laminates with three loops have been conducted and used to validate the accuracy of the multi-loop models, cf. Fig. 4 and [1]. The maximum loads of the simulation results agree well with the experimental results of the tested multi-loop laminates.

The experimental and simulation results presented in [1] have underlined the following benefits of reinforcing holes by winded multi-loop carbon rovings: (1) stiffness increase and reduction of non-linear deformation before macroscopic failure (presumably resulting in a better fatigue behavior), (2) increase of the maximum load and (3) increase of the overall failure energy and, thus, safety improvement in crash applications. In the following section, different multi-loop configurations with varying geometric design are evaluated in terms of their improved load bearing capacity.

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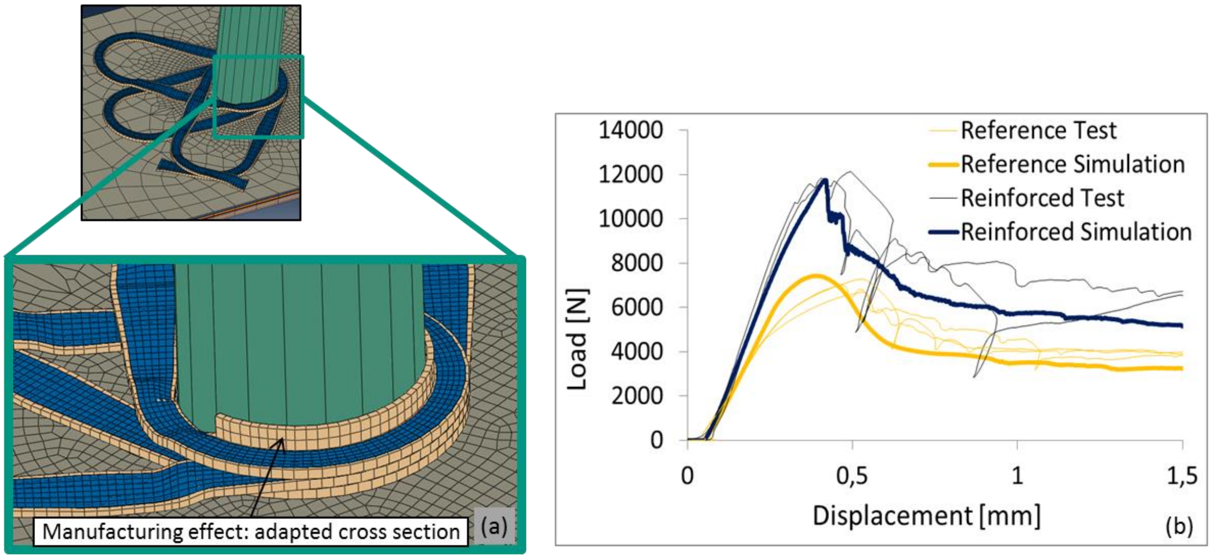

Figure 4. (a) FE model of an example multi-loop configuration and adapted cross section according to observed manufacturing effects, (b) load-displacement-curves of an open-hole reference-laminate (bold light line) and a reinforced laminate (bold dark line), both compared to experimental tests [1].

4. Investigation of various multi-loop configurations and evaluation of their structural response

By means of the mesoscopic model for multi-loop laminates presented above, an iterative adaption can be performed to optimize the design of multi-loops and to derive general design guidelines to reinforce bolt-loaded laminates with winded rovings, see Fig. 5.

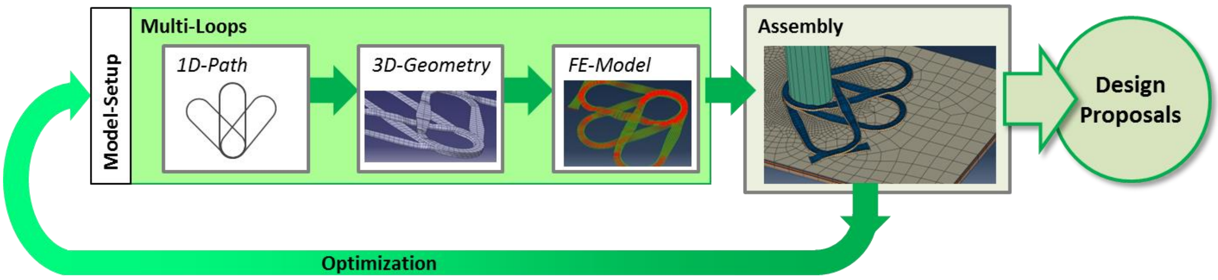

Figure 5. Workflow for design optimization of multi-loop reinforcements in open-hole laminates.

By utilizing the model setup established above, 22 variants of multi-loops have been investigated and compared. A selection of the studied configurations is shown in Fig. 6. Variant V1 is the basic loop which was used for experimental validation in Section 3, cf. Fig. 4. V2 and V3 use the same path as V1, but multiple times. V5 to V7 consist of one, two or three slings only in 0°-direction. V8 to V10 use rovings solely as turns, without any slings. V11 combines V5 and V8. V12 to V14 have two slings in +45° and -45° direction, without a sling in 0°-direction.

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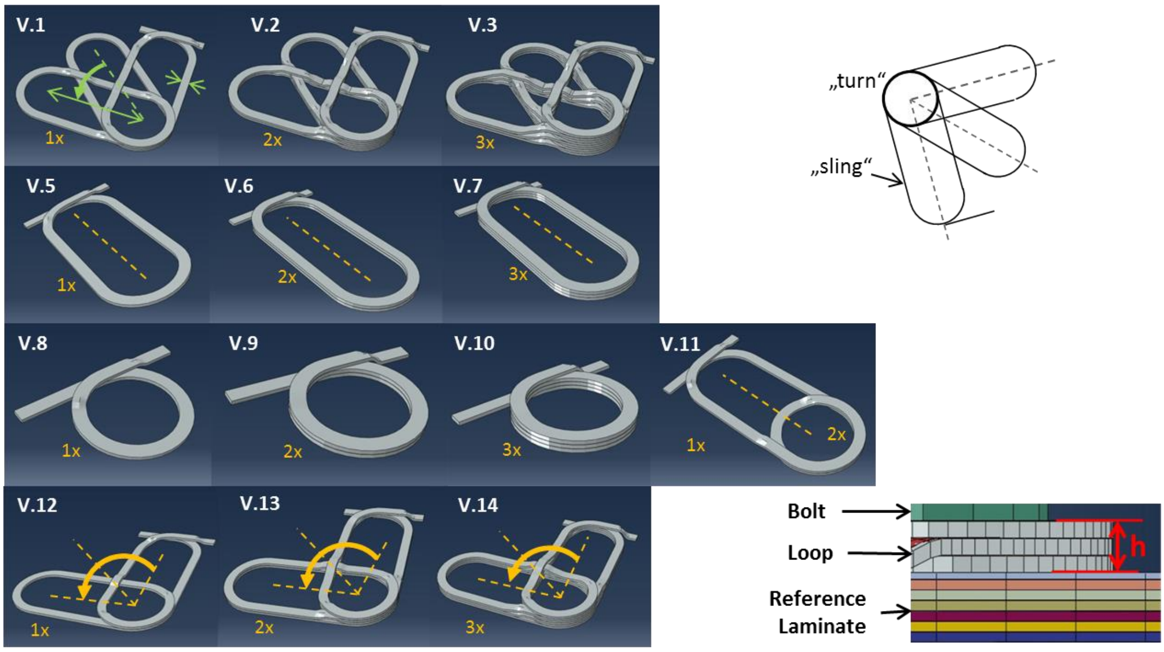

Figure 6. Selected loop variations, orange lines show differences compared to variant V1, orange numbers show number of loops; bottom right: region of the turns near the bolt, the height h of the loops is important for the structural response.

The load-displacement curves of the reinforcement variants V1 to V3 (with one, two and three layers of reinforcing loops, respectively) are displayed in Fig. 7 and show an increasing failure load with increasing number of loops. The gradient of this strength increase, however, decreases for more loops. Damage progression takes place at a higher load-level and, thus, the amount of absorbed energy increases, if the number of loops increases. Furthermore, the stiffness of V3 with three loops remains constant almost up to total failure, while V1 with only one loop softens much earlier. Overall, it is recognizable, that the height of the turn near the bolt has the greatest impact on the structural responses, if only a few turns are used. If the amount of turns is extended, it becomes more significant to transfer the load properly into the slings than increasing the height h, cf. Fig. 10.

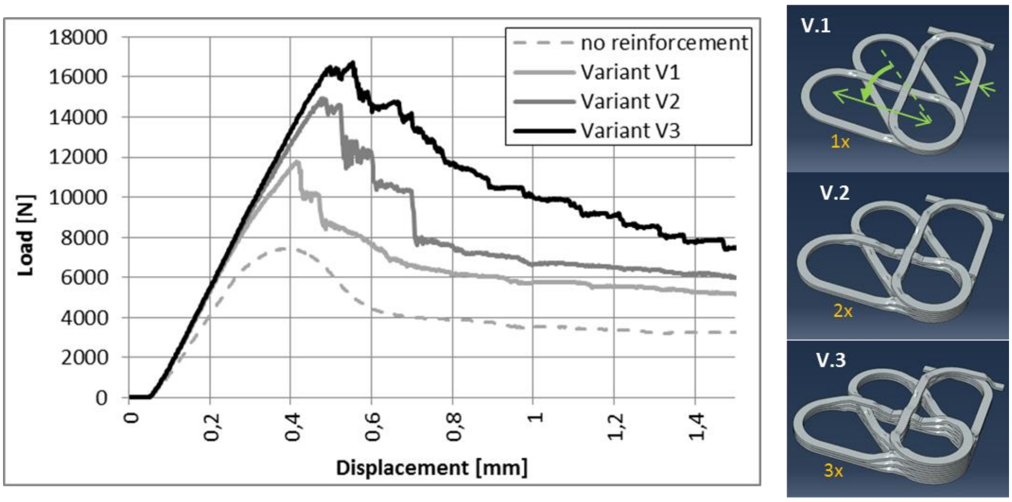

Figure 7. Load-displacement curves of variations V1 to V3, compared to non-reinforced open-hole laminate.

Fig. 8 shows the shear stress distribution in the first layer of the unreinforced open-hole laminate (Fig. 8a) and of the reinforced laminate variant V1 (Fig. 8b) at a bolt load of 4000 N. Due to reinforcement,

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the maximum stress decreases from 63 MPa to 49 MPa (regions (i) in Fig. 8a and 8b). However, in a certain distance from the bolt (region (ii)), the impact on the shear stress distribution is only small. This indicates that the major influence for the structural benefit occurs near the bolt in the turns and not due to the slings themselves. As shown in Fig. 8c, the load is actually transferred into the loops, which causes fiber tension in the slings and achieves a stiffness increase of the hole bearing.

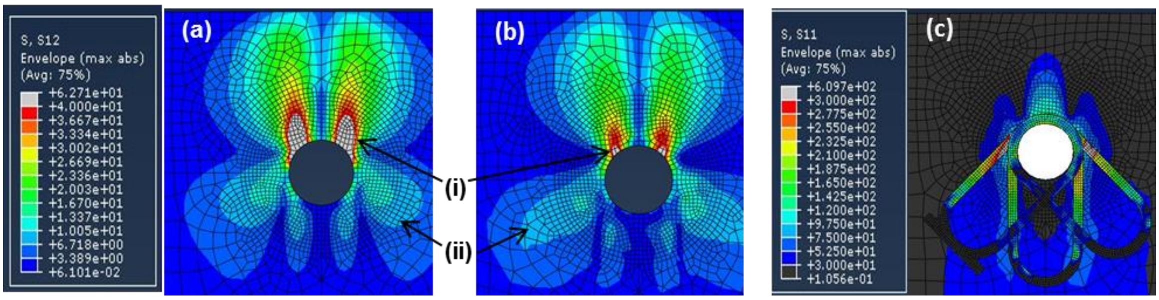

Figure 8. Comparison of in-plane shear stresses within the top-layer of the unreinforced reference-laminate (a) and of the reinforced laminate variant V1 (b) at a bolt load of 4kN, in-plane normal stresses in the reinforcement of variant V1 (c).

Fig. 9 shows a comparison between the structural responses of reinforcement variants V6, V9 and V11. All three variants consist of two turns around the bolt and, thus, have the same reinforcement height h. The difference between the three variants is the size of the slings. While variant V6 includes two long slings, variant V11 has only one and V9 has no long sling, but only turns. The maximum forces and the curve progressions show that the size of the slings has almost no influence on the failure load (i) and on the amount of energy absorption. However, there is a slight influence on the stiffness: Variant V9 softens earlier (ii) due to missing slings which would transfer the tension load further into the structure.

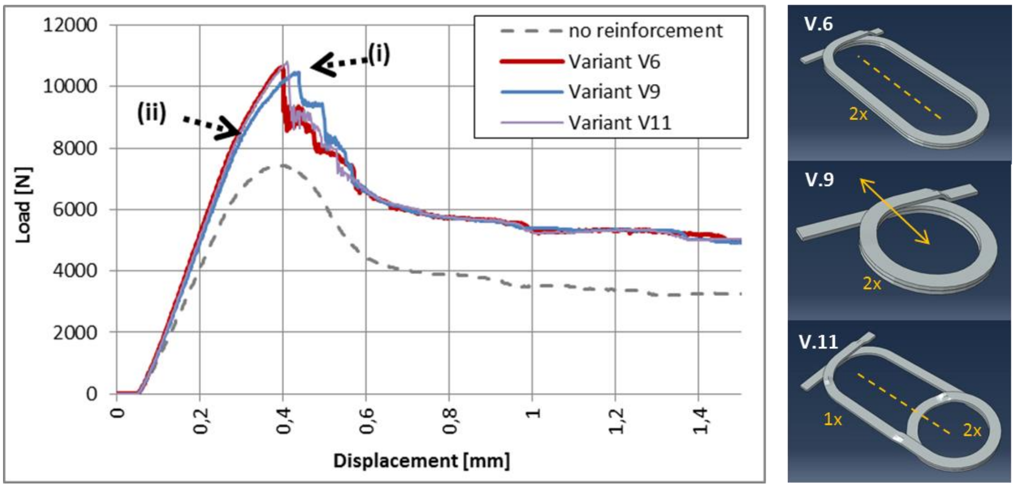

Figure 9. Load-displacement-curves of reinforcement variants V6, V9 and V11with same number of loops: showing negligible influence of the size of the slings on the failure load (i).

A general comparison for increasing loop numbers and different types of turn-sling-combinations is illustrated in Fig. 10. It is obvious that the failure load generally increases for increasing number of loops and, thus, for increasing height h of the reinforcement. If only pure turns are winded around the bolt, without any slings (V8 to V10), the increase of failure load drops rather rapidly, cf. Fig. 10 (i). This is caused by a detachment of the loops from the base laminate, which is the ultimate failure mode if a certain number of turns is reached. When comparing the basic three-loop reinforcement (V1-V3,

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analyzed in Section 3 with the reinforcement of single 0°-loops (V5-V7) and of double ±45°-loops (V12-14), there is nearly no difference noticeable for the considerable load increase with increasing height of the reinforcement. At a reinforcement height of 2.7mm, the failure load has increased by about 50%, from 7,4kN up to more than 11kN. If the height h exceeds 4mm, the load increase decelerates, tending to a maximum failure load (ii). As for (i), this load limit is caused by a detachment of the loops from the base laminate, which becomes independent of the reinforcement height, if a limit height is exceeded.

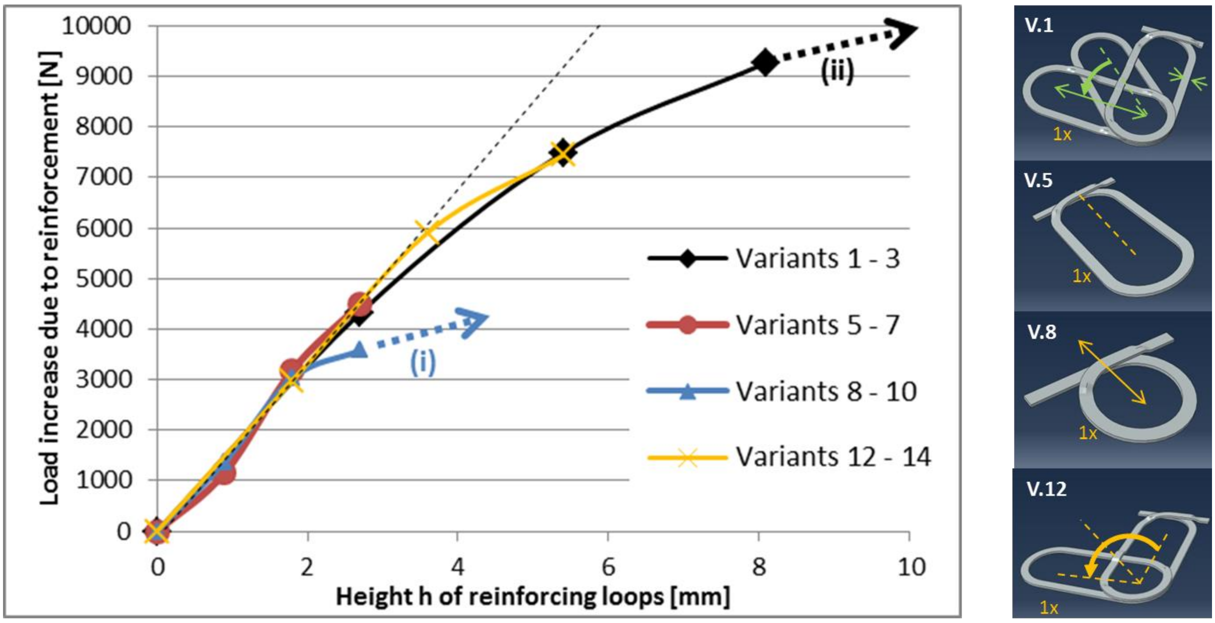

Figure 10. Comparison of different types of turn-sling-combinations in a load-height diagram: Increasing failure load for increasing height of the reinforcement: moderate load increase (i) without slings (V8-10) and raised load increase (ii) for one, two or three slings (V1-3, 5-7, 12-14), cf. Fig 6.

5. Conclusions and design suggestions

An open-hole laminate which is loaded by a bolt, leading to bearing stresses, can be reinforced by winded carbon roving loops. Experimental and numerical studies have shown that the failure load can be increased considerably with increasing number of loops. The winded loops absorb the load and relieve the hole. As a consequence, the initial region of linear material behavior before failure is extended, which indicates an improved dynamic behavior for fatigue. Furthermore, the energy dissipation in case of crash loads is increased.

For designing multi-loop reinforcements, the number of loops in thickness direction (increasing the height of the reinforcement), the number of loops in in-plane direction (forming a multi-loop rosette) and the angle and shape of the loops can be varied. According to the performed parameter studies and stress analyses, the following conclusions and design suggestions can be deduced:

- The height of the turns near the bolt has the dominant impact on the structural responses, if up to three or four turns are used. This positive impact, however, diminishes for a higher numbers of turns. Thus, more than 4 turns of a 12k roving around the bolt are not recommended as they do not significantly further improve the load-bearing capacity.
- The length and the number of loops (slings) within a multi-loop rosette have a minor effect on the structural response, as long as the number of loops in thickness direction is small. If the number of loops in thickness direction is chosen to be larger than two, pure turns (without slings) provide no further load increase due to a detachment of the loops from the base

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laminate. Thus, in the case of more than two turns longer slings around the bolt are more favorable to further improve the load-bearing capacity.

- To transfer the bearing load from the bolt into two single slings, the slings should be arranged in tangential direction starting from the two areas of maximum bearing stress.

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