An approach to validate simulation models for the optimization of fiber-reinforced bead patterns

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1 Summary

This contribution presents an approach to validate the simulation models of an optimization method, which supports the product developer in the determination of the initial design of a fiber-reinforced bead pattern. Usually bead optimizations are carried out by varying geometrical parameters, e.g. bead height and width or position. In this contribution an optimization method is presented to reinforce beaded sheet metal components through the targeted integration of fiber-reinforced polymers in the top flange area of the beads. Because the concept of fiber-reinforced beads is not sufficiently understood, it is necessary to investigate these structures experimentally as well as numerically. In order to conclude from simulation models to the physical behavior, it is necessary to validate these models. Since it is not feasible to compare every simulation model generated throughout the optimization with a respective physical specimen, another approach is needed to validate the method. Therefore, this contribution proposes such a validation approach for the presented optimization method.

2 Introduction

In the light of climate change, automotive or aircraft manufacturers, for example, are faced with the challenge of increasing the efficiency of their products in order to comply with legal requirements for achieving climate targets. To reduce the fuel consumption and thus the harmful emissions of a system, one possibility is to minimize the moving mass. For example, a saving of 100 kg in an automobile results in a fuel saving of 0.5 l per 100 km and at the same time a reduction in CO_2 emissions of 12 g/km [1]. For this reason, the principle of lightweight design is nowadays widely used in the development of products. One possible lightweight design solution is the insertion of beads in thin-walled structures as a stiffening design element. A bead describes a channel-like depression or elevation that is inserted in flat or curved sheet metals and has a small ratio of height to length [2]. Fig 1 shows an exemplary bead cross section. The insertion of the bead causes an increase of the second moment of area I due to the changed cross section, resulting in a higher bending stiffness. The increased bending stiffness enables the reduction of the sheet metal's thickness, thus reducing its mass. To maximize the stiffening effect of a bead, its orientation needs to be parallel to the highest main bending stress [3]. This means that the optimal bead design is depended on the load case. Since products are usually used in various load cases, individual product variants would be necessary for an optimized design. This would require separate tools for the production of each variant, which is uneconomical. However, a uniform design based on the load case with the highest load leads to an oversizing of the component in relation to the other load cases. This results in the need for a solution to generate variants based on a basic component.

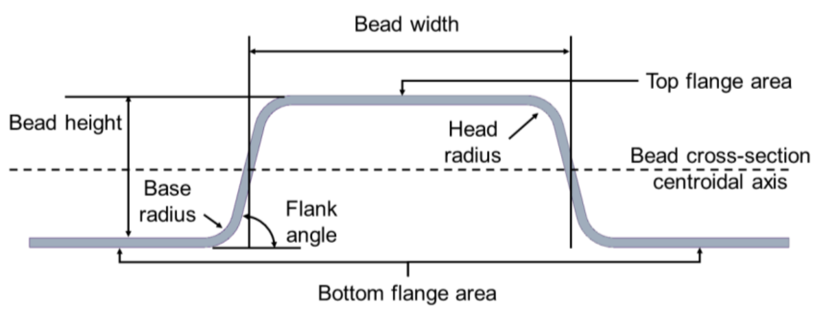

Fig 1
Cross section of a bead according to Emmrich [3]

One approach to generate variants without adjusting the position of the beads or the bead cross section is the load-specific additional lamination of unidirectional fiber-reinforced polymers (UD-FRP) into the top flange area of the beads with the fibers aligned along the trajectory of the bead. This allows the high mass-specific stiffness of this material group to be exploited. Furthermore, by varying the number of UD-FRP layers, the degree of reinforcement can be adapted to specific load cases. For a better contact, an additional bead is introduced in the top flange area of the bead, shown in Fig. 2. Since adding material to the bead counteracts the reduction of mass, it is important to apply the reinforcement locally in a targeted manner. However, this results in a problem for the product developer with a high number of possible solutions, depending on the degree as well as the position of the reinforcement, which makes a manual determination of an optimized reinforcement pattern inefficient. Therefore, a computer-aided optimization is developed, that supports the product developer in the determination of an initial design of a fiber-reinforced bead pattern. Since the use of fiber-reinforced beads is hardly investigated, it is of great importance to validate the used simulation models as well as the optimization method.
For this reason, this contribution presents the optimization method in development as well as an approach to validate the overall method.

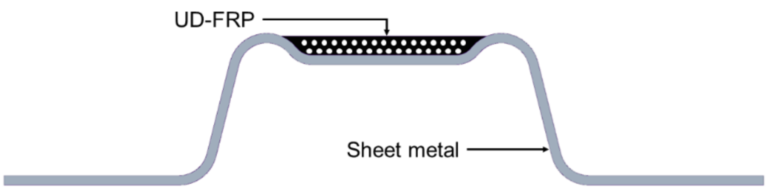

Fig. 2
Cross section of a bead with an additional bead in the top flange area to incorporate UD-FRP

3 State of the Art

To support product developers in designing beaded sheet metal components, design catalogs were developed in the 1970s [4]. These catalogs and guidelines are helpful for simple geometries and loads, but are only limited applicable for more complex components and load cases [5]. In recent years, numerical optimization methods are used more commonly for bead designs. It can be shown, that with the numerical optimization stiffer designs can be realized [6]. Commercial tools offer different algorithms to numerically calculate optimized bead patterns. For example, Tosca structure offers a general sensitivity-based optimization as well as a condition-based optimization [7]. The condition-based algorithm is based on the bending hypothesis described in [3]. With this algorithm, the beads are oriented along the main bending trajectories. The results from these algorithms are generated by moving the nodes of the FE model used in the optimization perpendicular to the surface. Since these results still need an interpretation by the product developer and a manufacturability of the design is not always given, Majic et al. developed a manufacturing-integrated optimization method to generate manufacturable bead designs [8].

4 Optimization method for fiber-reinforced bead patterns

Currently an optimization method is developed to support the product developer in determining a fiber-reinforced bead pattern based on the main bending stress trajectories. This method can be separated into an initialization and an optimization step. In the initialization step, a detailed finite element (FE) model of a beaded sheet metal structure with UD-FRP in the top flange area is generated to numerically investigate the properties and behavior of the material combination. If multiple degrees of reinforcement are considered, e.g. by changing the number of UD-FRP layers, an individual FE model is necessary for every degree. Since the calculation time of this model increases with the level of detail, e.g. the consideration of contact behavior or material anisotropy, an optimization based on the detailed FE model would be time-inefficient. Therefore, a substitute FE model is implemented, where the top flange area of the beaded structure is replaced by simple shell elements. To replicate the behavior of the detailed models, these shell elements are assigned with a specific material parameter set for every degree of reinforcement. These material parameter sets are transferred to the optimization step of the method and used as the design variable. Fig. 3 shows the detailed and the substitute FE models implemented in ABAQUS.

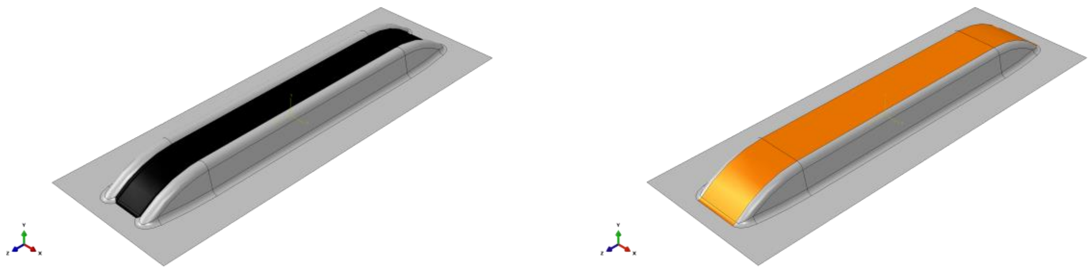

Fig. 3
FE models used in the initialization step: detailed FE model with UD-FRP in black (left), substitute FE model with shell elements in orange (right)

The input for the optimization is the FE model of a beaded sheet metal component. At first, the top flange areas of the beads in the sheet metal component are partitioned into several sections along the length of the bead. Afterwards, the material parameter sets are assigned to each section individually. During the optimization, these assignments are varied iteratively to determine an optimized configuration of material parameter sets under the consideration of various constraints, e.g. a maximum amount of reinforcement. Since the number of possible solutions increases with the number of sections as well as the degrees of reinforcement, an evolutionary algorithm is implemented for a time-efficient optimization. The result of the optimization is an optimized initial design of a sheet metal component with a fiber-reinforced bead pattern. Fig. 4 shows the flowchart of the described optimization method.

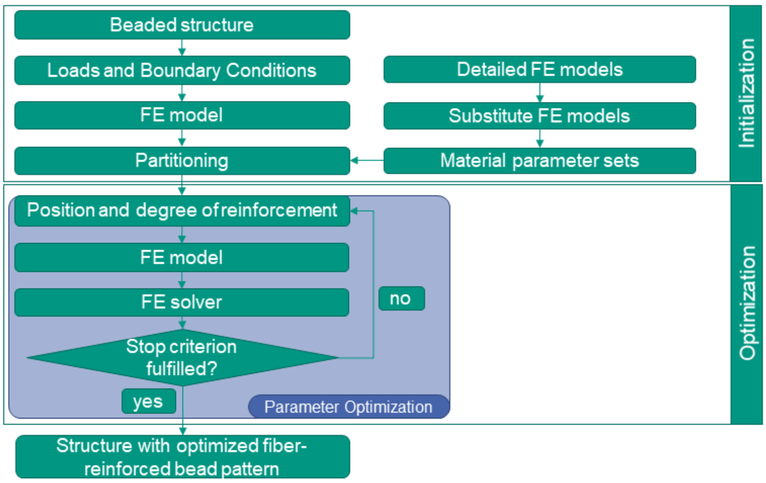

Fig. 4
Flowchart of the optimization method

Additionally, this method will be used to generate a basic sheet metal component that can be adapted to various load cases. Therefore, the procedure needs to be carried out for every relevant load case. The results are then combined to define the positions of additional beads in the basic component. Afterwards, the optimized reinforcement patterns for every individual load case is calculated.

5 Validation approach

To draw conclusions from the determined initial design, it is inevitable to validate the optimization method. Since it is not feasible to manufacture every configuration computed during the optimization, an alternative approach is necessary. The validation approach proposed in this contribution is based on the concept of validation of individual methods and simulation models used in the optimization method.

At first, the combination of sheet metal and UD-FRP without geometric effects is investigated. Therefore, a three-point bending test is carried out with a simplified specimen, where a sheet metal of the dimensions 10mm x 80 mm x 1mm is laminated with UD-FRP. The specimen is positioned in the test bench with the UD-FRP layer on the top side. The recorded force-displacement curve as well as the identified moment of failure are compared to simulation results carried out with a FE model of the specimen. With this comparison, the material parameters of the FE model are iteratively adapted and

fitted. Afterwards, the procedure is repeated with the sheet metal on the top side and the UD-FRP on the bottom side. The experiment is carried out with various samples to investigate statistical uncertainties. If the experimental and simulative results match, the material model is validated.
Secondly, the detailed FE model used in the initialization step is validated. Again, a three-point bending test is used. To verify the FE model of the fiber-reinforced beaded sheet metal structure, a specimen of a beaded sheet metal with UD-FRP laminated in the complete top flange area is investigated. After the verification by comparing the force-displacement curves was successful, the procedure is repeated with a test specimen, in which the top flange area is only partly laminated. The physical experiments are once again carried out using various samples. If the curves once again correlate, the detailed model can be viewed as validated.
The next step is the verification and validation of the substitute model. Therefore, the substitute model is implemented to resemble the specimen validated in the last step. Afterwards, the two FE models are compared by investigating the deformation at the individual nodes under a given load. The material parameter set of the shell elements used to replicate the top flange area is iteratively adapted until the parameters are appropriately fitted. To further validate the substitute model, the procedure is repeated with a varied bead length to change the influences by geometric properties. Again, if the results are comparable, the substitute model can be viewed as validated.
After the FE models used in the initialization step have been validated, it is necessary to also validate the optimization. The optimization method is verified by using it on a simple component under a given load. The used model is a simple plate that is clamped on one side and a bending load on the opposite side. At first, no constraints are applied, so the result should be a maximum reinforcement in every section of the top flange area. Subsequently, the procedure is repeated under constraints. If the result in the first run is correct and the constraints are met in the second run, the method is considered verified.
In the last step of the validation, the method is applied to a more complex demonstrator component. The determined fiber-reinforced bead pattern from the optimization is then applied to a physical version of the demonstrator. Afterwards, physical experiments are carried out and compared to the simulation results. If these results are equivalent, the overall optimization method is validated.

6 Conclusions

This contribution proposes an approach to validate an optimization method that supports the developer in the determination of fiber-reinforced bead patterns, depending on the position and degree of fiber-reinforcement. Within this approach, the overall optimization is validated by validating the individual simulation models and methods used in the overall optimization method. The presented optimization method enables the generation of a basic component that is adjustable to various load cases, resulting in numerous component variants.

7 Acknowledgements

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