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Method for considering the process chain in the design process of clinched components

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Abstract. To ensure a high quality design of joined components, it is essential to consider the joining process chain since deviations in the process chain can lead to failure of the component. Since eliminating the cause of process deviations can be very cost-intensive, it is desirable to ensure component and joining safety by making small changes. A method to regain all safety factors after a change in the process chain by making minor adjustments in the joining process and the design is presented here. The method is demonstrated on a clinched component consisting of a U-profile and a strike sheet.

Introduction

If any deviations and disturbances in the joining process chain occur, the real operational loads on the joints of joined components do not correspond to the calculated loads from the design and dimensioning phase [1]. For this reason, increasing efforts are made to optimize manufacturing tolerances [2]. It is further known that different joint stiffnesses lead to load redistribution between the joints [3]. Different joint stiffnesses are obtained for example, when clinching sheets with the same process parameters, but different deformation states in the joining area before joining [3]. In addition, robustness analyses are often carried out for safety reasons, in which it is assumed that a certain proportion of the joints are broken. Such analyses aim to achieve the desired component properties despite the statistically distributed failed joints. [4] Therefore, despite the use of simulation, the number of joints and the value of the safety factors tends to be higher than required. A more lightweight design with lower safety factors would be possible if the cause-effect relationships between the process parameters on the loads on the joints are describable and predictable. Additionally, the process and quality variables have to be continuously checked during manufacturing to identify deviations. When designing and dimensioning a high quality joining design with low safety factors for a versatile joining process chain, three challenges arise.

Firstly, the cause-effect relationships must be identified. Secondly, these relationships must be exploited to increase the degree of utilization as much as possible at every joint, and thirdly continuous monitoring over the whole process chain must be implemented. This paper demonstrates how deviations can be considered in virtual product development and countermeasures can be taken. Thus, a list of causes and countermeasures can be shared with the manufacturing personnel to ensure high product quality.

Method

The method shown in Fig. 2 c) is used to design a clinched component with consideration of a versatile joining process chain. The method is based on cause-effect relationships between influencing parameters on the loads on the joints. The geometry of the joint is an influencing factor and is affected by many parameters. For example, the existing deformation state and sheet thickness in the joining area before joining [3], the used tools [5] and the joining process parameters [6] influences the final joint geometry. The deviating joint geometry leads to a

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difference in stiffness, maximum elasticity and maximum force in destructive characterization such as shear lap or head tension tests [3]. Some of the influencing parameters on the clinched joint properties are mentioned in Fig. 2 a1). In addition, the loads on a joint also depend on external geometry-related component-dependent influences. In [7] it is shown that the load on a clinched joint depends on the geometry in the proximity of a clinched joint. In the numerical analysis of [3], it is illustrated that the variance of the load on a clinched joint in components of pre-deformed sheets depends on both, the global sheet thinning and the change in the stiffnesses of the clinched joints due to local sheet thinning. Further factors influencing the load on a joint are the number and distribution of the joints [8], as well as the components' geometry and the applied load and boundary conditions. Some influence values on the mechanical behavior of a clinched joint are listed in Fig. 2 a1). In Fig. 2 a2) some influences values on the joints' loads are named.

For this purpose, in numerical evaluations the variables of Fig. 2 b) were used to describe the loads on the joints and their scatter. In finite element simulations of joined components, joints are represented with equivalent elements in which the applied load is described with a three-dimensional force and three-dimensional moment vector. The equivalent force consists of the components f_r, f_s and f_t. Since the torsional moment of clinched joints is assumed to be zero, the bending moment leads to a normal force component which, when added to the force f_r, gives F_N. This equivalent force is shown in Fig. 2 b3). The sum of the shear force components f_s, f_t gives F_S. The load angle α is enclosed by F_S and F_N. The angle between the s-axis and F_S is the orientation angle β. With the absolute values F_S and F_N, a load on a joint can be drawn in a shear force normal force diagram, as shown in Fig. 2 b4). The maximum elastic force (black curve in Fig. 2 b4)) and the maximum force (grey curve in Fig. 2 b4)) that can be applied to the joint depending on the load angle α are defined with limit curves. These limit curves are either created by connecting measured points from experimental tests under shear, normal and mixed loading or are approximated by mathematical formulas.

The scatter in a joint can be shown by plotting the different loads on a joint in a shear force-normal force diagram, as in Fig. 2 b5). A hull curve can be derived for the resulting point cloud, which can be approximated by an ellipse. By expressing the ellipse shape and orientation by the center, the minor and major semi-axis and the ellipse orientation angle Θ, global statistical evaluations can be performed as shown in [1].

The cause-effect relationships from Fig. 2 a) and the evaluation measures from Fig. 2 b), are transferred to the design method shown in Fig. 2 c). The input of the method is an initial design of a clinched component, dimensioned with its nominal values. In the first step a change in the joining process chain is assumed. Either the properties of the sheet metal parts, the properties of some or all joints or the properties of joints and sheet metal parts are changed. Subsequently, virtual component testing is performed using finite element simulations with adjusted sheet and joint properties. After the calculation, it is checked whether the component meets its requirements during the entire test sequence. If the joined component does not meet its specifications, an adjustment is made. Either one or more joints (left cycle in Fig. 2 c)), the number and distribution of joints or the component geometry (right cycle in Fig. 2 c)) are changed.

Demonstration of the method on a clinched component

The method is demonstrated for elastic dimensioning. In this case, two sheet metal parts made of HCT590X with a sheet thickness of s_0=1.5 mm are joined. The geometry of the component and the load case are shown in Fig. 1. The corresponding values can be taken from Table 1.

For dimensioning, the clinched joint is characterized by experimental shear lap and head tension tests. The maximum force, the maximum elastic force, and the stiffness are determined from the obtained mean force-displacement curves for both set-ups. The coefficient of determination R^2 for the stiffness fit was set to 0.995. The obtained values can be taken from Table 2. In the simulation

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model, depicted in Fig. 1 b), the component is meshed with shell elements with a mean edge length of 1 mm. The material behavior of the profile and the strike sheet is modeled with a Hocket-Sherby constitutive model, determined with tensile and layer compression tests. The clinched joints are represented by a beam and a rigid spider with a diameter of 10 mm. The equivalent stiffnesses are obtained by curve fitting and are also presented in Table 2. All simulations are calculated using the implicit solver of LS-DYNA R13.

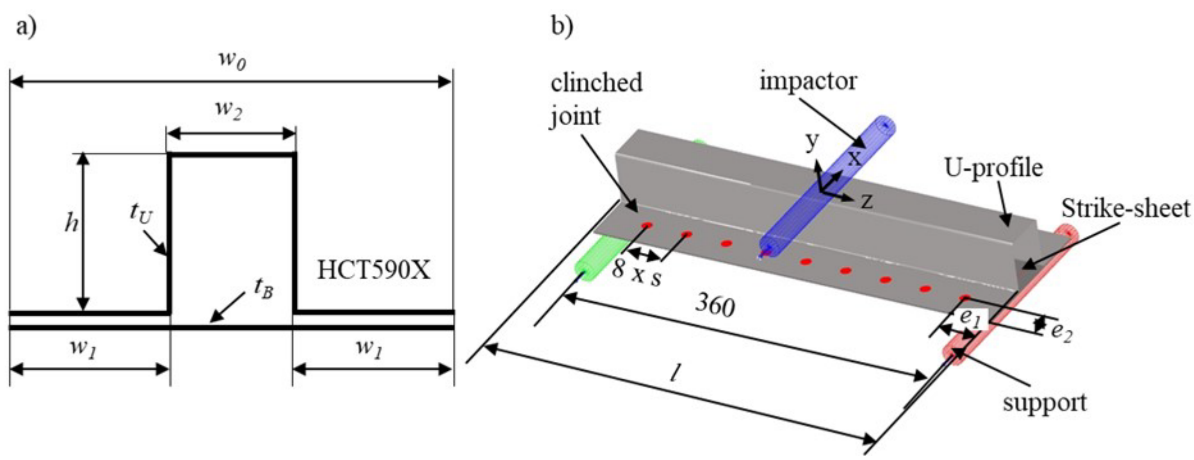

Fig. 1: a) Geometry of the joined component in section view b) FE-model and load case

Table 1: Information of the initial configuration

<table>
<tr><td colspan="2">Initial Geometry of U-Profile</td><td colspan="3">Joining design</td><td colspan="4">Clinching Tool</td></tr>
<tr><td></td><td>distance [mm]</td><td colspan="2">number of clinched joints</td><td>18</td><td colspan="2">punch diameter [mm]</td><td colspan="2">8</td></tr>
<tr><td>h</td><td>50</td><td colspan="2">e_1 [mm]</td><td>40</td><td colspan="2">die diameter [mm]</td><td colspan="2">10</td></tr>
<tr><td>w_1</td><td>50</td><td colspan="2">e_2 [mm]</td><td>25</td><td colspan="2">die depth [mm]</td><td colspan="2">1.6</td></tr>
<tr><td>w_2</td><td>40</td><td colspan="2">s [mm]</td><td>40</td><td colspan="4">TOX label: TOX A50100 / TOX BD8016</td></tr>
<tr><td>t_U</td><td>1.5</td><td colspan="7">Load Case</td></tr>
<tr><td>l</td><td>400</td><td colspan="2">support distance [mm]</td><td>360</td><td colspan="2">diameter of impactor and support [mm]</td><td colspan="2">10</td></tr>
<tr><td colspan="3">Geometry of Strike Sheet</td><td>w_0 [mm]</td><td>140</td><td>l [mm]</td><td>40</td><td>t_B [mm]</td><td>1.5 or 1.3</td></tr>
<tr><td colspan="2">Specification</td><td colspan="2">minimum impactor force [kN]</td><td>14</td><td colspan="2">minimum impactor depth [mm]</td><td colspan="2">3</td></tr>
</table>

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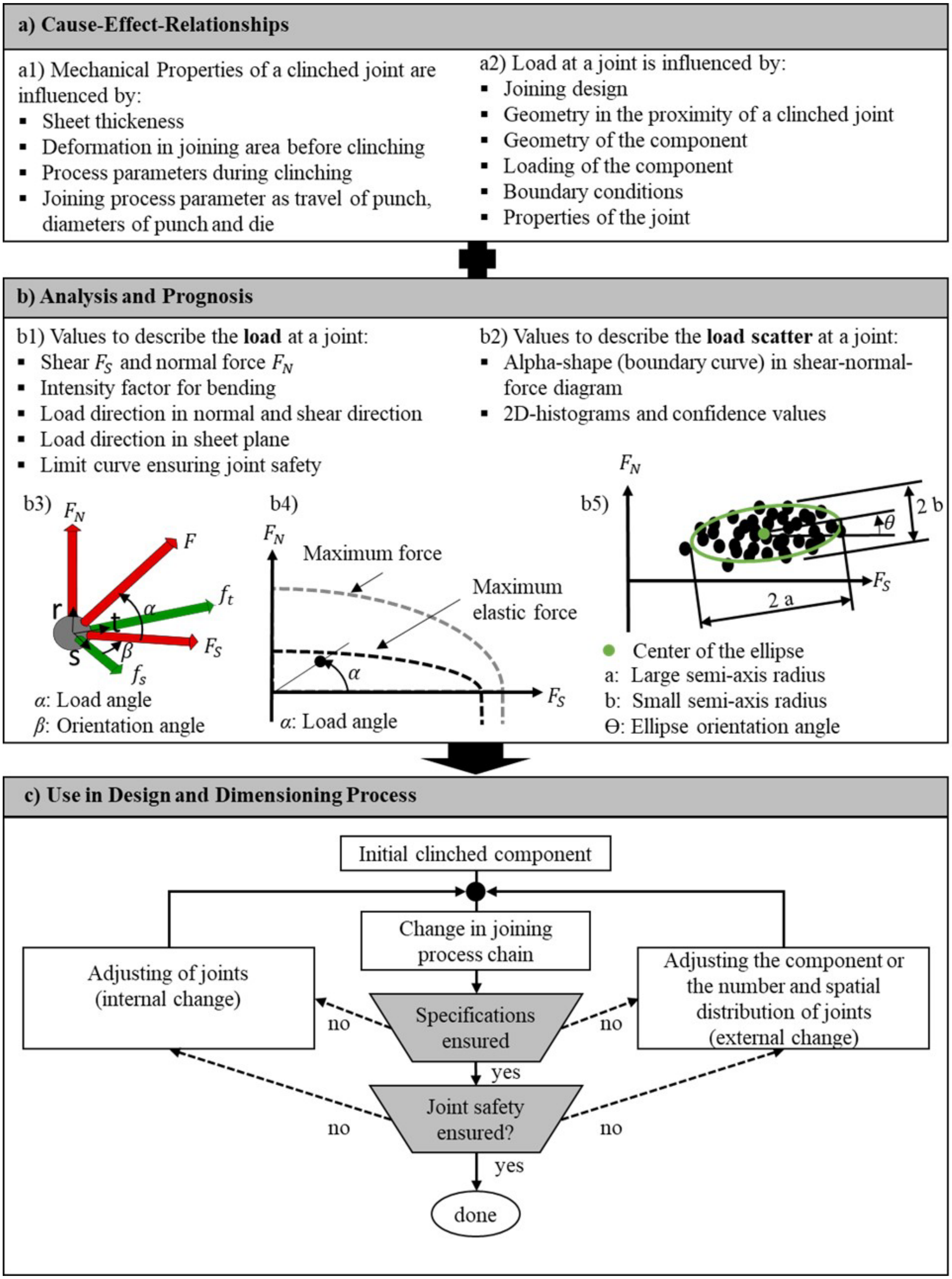

Fig. 2: Design Method for considering the process chain for a clinched component a) Cause-effect relationships b) Analysis and Prognosis c) Method

The property of the clinched joint for the combination of two 1.5 mm thick sheets are determined experimentally, as written before. In Table 3 the used equivalent stiffnesses and the

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maximum elastic force for combinations of two 1.3 mm thick sheets are listed. From the numerical investigation of [3] it can be seen that for a sheet thickness combination of 1.27 / 1.27 mm reduced by pre-stretching, the equivalent normal stiffness is reduced by approx. factor 0.4 and the equivalent shear stiffness by approx. factor 0.6. The prerequisite in this research was that the joining process parameters remained constant. It is also assumed that the maximum elastic forces are reduced by the same factor as the stiffnesses. Moreover, the same values are assumed for unequal pairings of 1.5 mm and 1.3 mm thick sheets as for 1.3 mm / 1.3 mm combinations. For a precise analysis these values must be determined experimentally for undeformed sheets and for the combinations of different sheet thicknesses for both joining directions separately.

Table 2: Properties of the clinched joint when joining two sheets with a thickness of 1.5 mm

Normal stiffness	~ 1670 N / mm
Shear stiffness	~ 22000 N / mm
Maximum elastic normal force	~ 700 N
Maximum elastic shear force	~ 3000 N
Maximum normal force	~ 2600 N
Maximum shear force	~ 4200 N
Equivalent normal stiffness	7700 N / mm
Equivalent shear stiffness	30250 N / mm

Table 3: Equivalent properties for the clinched joint in simulation for combinations with at least one sheet thickness of 1.3 mm

Equivalent normal stiffness*	3080 N / mm
Equivalent shear stiffness*	18150 N / mm
Maximum elastic normal force**	350
Maximum elastic shear force**	1800

* plausible estimation
** assumption

In Fig. 3, the limit curve for the maximum elastic force is approximated by the maximum elastic shear and the maximum elastic normal force. The maximum elastic shear is plotted on the abscissa and the maximum elastic normal force on the ordinate. Then, these points are connected in the first quadrant with an elliptic equation according to Eq. 1 and Eq. 2. In the fourth quadrant the limit curve is parallel to the ordinate and is described by Eq. 3 An internal change in a joint shifts the limit curve in the diagram and an external change leads to a different position of a point in the diagram.

$$F_S = F_{S,\ max,\ i} \cos(\alpha) \qquad \textit{for} \qquad 0° \leq \alpha \leq 90° \tag{1}$$

$$F_N = F_{N,\ max,\ i} \sin(\alpha) \qquad \textit{for} \qquad 0° \leq \alpha \leq 90° \tag{2}$$

$$F_N = F_{N,\ max,\ i} \qquad \textit{for} \quad -90° \leq \alpha \leq 0° \tag{3}$$

The method is demonstrated by considering sheet thickness thinning in the process chain. The requirement criteria for the component is, that it has to withstand an impactor displacement and an impactor force. Neither at an impactor force of 14 kN, nor at an impactor displacement of 3 mm the joints should be loaded plastically, but a local plastic flow of the material in the U-profile directly under the impactor is permissible. The requirements are stated in the last row of Table 1.

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First, the load case is simulated with the initial design (Config. 1). Then, the sheet thicknesses of the strike sheet (Config. 2) and of the profile (Config. 3) are altered.

Configuration 1 (Initial Design):

U-profile and strike sheet thicknesses of 1.5 mm each; initial stiffness and limit curve of the clinched joint when joining 1.5 mm thick sheets (Table 2)

Configuration 2 (Thickness of strike sheet altered):

U-profile with a sheet thickness of 1.5mm; strike sheet with a sheet thickness of 1.3 mm; reduced stiffness and limit curve (Table 3)

Configuration 3: (Thickness of profile altered):

U-profile with a sheet thickness of 1.3 mm; strike sheet with a sheet thickness of 1.5 mm; reduced stiffness and limit curve (Table 3)

Configuration 1 is the reference design for which the requirements and the safety in the joint design should be verified. Configuration 2 represents a sheet thickness deviation of the strike sheet and Configuration 3 of the U-profile. The reduction of both sheet thicknesses is very similar to Configuration 3, since the worst clinched joint properties are assumed anyway and the strike sheet stiffness has hardly any influence, as will be shown. Therefore, this configuration is not discussed. To ensure that not only a quarter of the joints are visible in the shear force-normal force diagrams, the joints are not positioned exactly symmetrical.

Results

The forces are evaluated up to an impactor travel of 3.0 mm. In Fig. 3 the equivalent forces at a displacement of the impactor of 3.0 mm are shown. The calculation of Config. 1 show that the requirements have been met. In Fig. 3a) all points lie within the limit curve. The analysis of Config. 2 shows that the four outer joints are plastically loaded at an impactor depth of 3 mm which is depicted in Fig. 3 b). It can be also seen that the equivalent forces in the clinched joints are significantly lower in the design with the reduced the strike sheet thickness (red crosses) than in the initial design (grey crosses). Nevertheless, four points lie outside the reduced limit curve, after the sheet thickness reduction. According to the method, the outer joints must be positioned closer to the impactor. After shifting the four laterally joints 15 mm further towards the center in the y-direction, the joining safety is regained, which can be seen in Fig. 3 b) (green crosses). To show that the joint loads can also be reduced by changing the geometry within the proximity of the joint, the reduction of the loads with circular beads is shown in orange in Fig. 3 c). The bead has a height of 1.2 mm, a width of approx. 3 mm and is inserted in a diameter of 15 mm around the joint. In the given case, however, the insertion of those beads is not sufficient to regain joining safety. When reducing the sheet thickness of the U-profile (Config. 3), the specification (Table 1) is not met since the force of 14 kN is not reached. Therefore, the height of the profile is increased by 5 mm. As a result, the targeted force level is reached again. The joint design can remain unchanged despite the reduced joint properties because all points lie within the limit curve shown in Fig. 3 d). Since there is no implementation of cause-effect relations between global bending and the joints' load, the increase of the profile height was calculated manually.

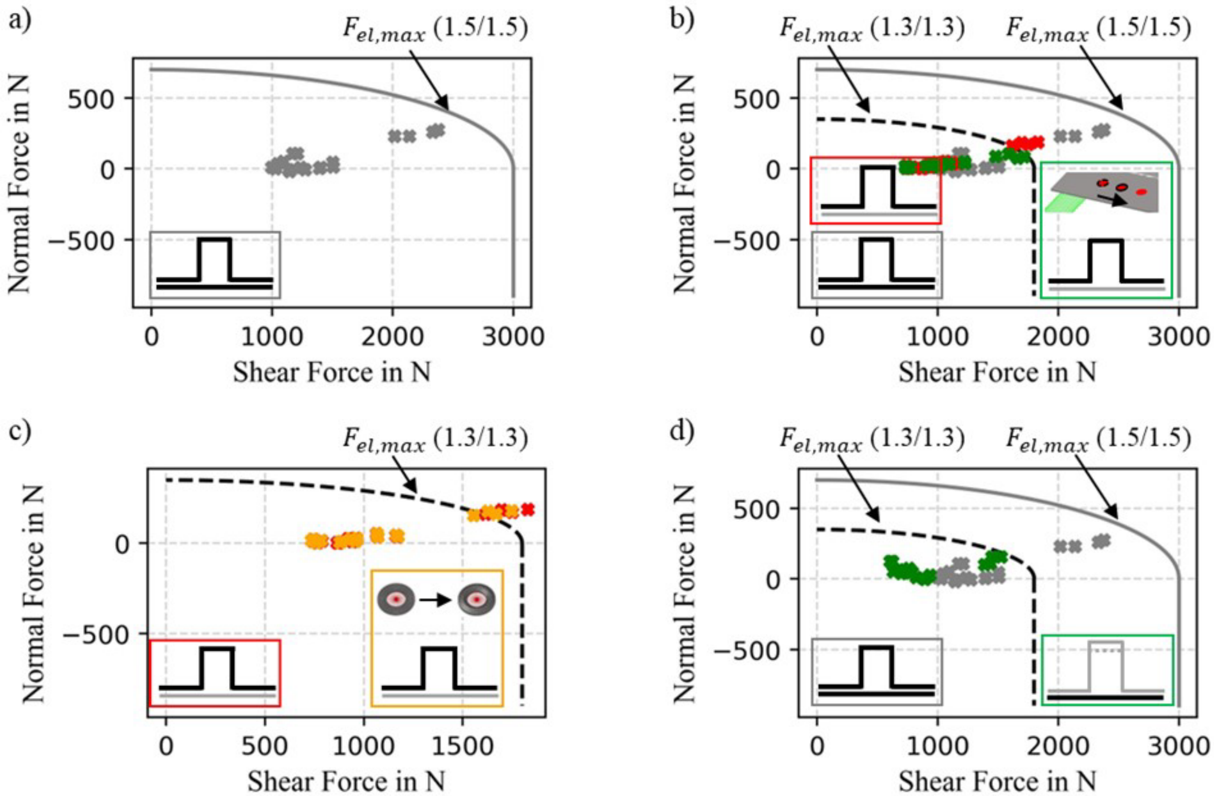

Fig. 3: Loads in the joints at an impactor depth of 3.0 mm a) Config. 1 b) Config. 2 - Optimized Design for a strike sheet with a thickness of 1.3 mm c) Config 2 - Inserting circular beads around the outer joints for a strike sheet with a thickness of 1.3 mm d) Config. 3 - Optimized Design for a U-profile with a thickness of 1.3 mm

Discussion

It was shown that with the presented method the versatile joining process chain can already be considered in the design phase. For the applicability of the method, it is essential that the cause-effect relationships are known and that the required data have been determined. In particular, the different mechanical properties of the resulting joints at different conditions in the joining area before clinching must be known. The method demands a huge amount of data, which increases when the method is extended for the non-linear dimensioning of joined components. As shown here, estimated assumptions can also be used, if no precise experimental data is available. The results are then, of course, more prone to error.

The geometry of the component can be changed either globally or locally. If utilizing the local component geometry in the proximity of the joint, linear beads can also be used in addition to circular beads. If linear beads are inserted, it must be considered that their effect depends not only on the load situation but also on their alignment to the joint. In addition to the option shown here of creating a list of countermeasures for manufacturing, when a deviation in the process chain is detected, the method can also be used to derive more robust designs, or to achieve more similar utilization rates in the joints.

Summary
With the presented method, it is possible to create a catalogue of countermeasures for production personnel on how to intervene in the component and joining design in the event of certain changes in the process chain to regain joining safety and to still met the component requirements. This ensures the manufacturing of high quality joined components despite deviations in the process chain. The method was demonstrated on a clinched component consisting of a U-profile and a strike sheet. At the same time, the method can also be used to obtain more robust designs, or to achieve more similar utilization rates in the joints.

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