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A Numerical Study on the Mutual Influence of Joint Orientation and Component Geometry in Non-Rotationally Symmetric Clinched Joints

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Abstract. Clinched joints with non-rotationally symmetric geometries exhibit orientation-dependent mechanical behavior that is commonly neglected in structural-scale simulations. Reuleaux triangle shaped clinched joints, in particular, show pronounced in-plane anisotropy depending on their orientation. While such effects have been studied at joint and specimen scale, their relevance at the structural level remains largely unexplored. In this work, the influence of joint orientation on the bending response of a joined structure is investigated using numerical simulations. A simplified joint replacement model based on the *CONSTRAINED_SPR2 point-connector formulation in LS-DYNA is employed, with parameters calibrated from previously obtained experimental force displacement data. A hat shaped profile structure subjected to three-point bending is analyzed in a parametric study considering variations in joint orientation, joint spacing, and profile geometry. The results show that joint orientation has little influence during the initial deformation phase but becomes increasingly significant at larger displacements, where joint behavior governs load transfer. Orientation dependent effects are found to influence the global force displacement response and local load redistribution among joints, with magnitudes comparable to those induced by changes in joint spacing and structural geometry. The findings confirm that joint orientation effects remain relevant at the structural level and should be considered in the design of structures assembled using non-rotationally symmetric clinched joints.

Introduction

Mechanical joining technologies play a key role in lightweight design, particularly in automotive and transportation applications where thin sheet metals and dissimilar materials must be joined efficiently, reliably, and at low cost[1], [2]. Among these technologies, clinching has gained widespread industrial acceptance due to its ability to join sheets without additional fasteners or thermal input, while maintaining good mechanical performance and process robustness[3]. Conventional clinch joints are typically rotationally symmetric, which results in largely isotropic mechanical behavior under in-plane loading conditions.

Recent developments in clinching technology, however, have led to the introduction of non-rotationally symmetric clinch joints[4], [5], [6]. Unlike conventional joints, these advanced geometries exhibit direction-dependent load-bearing characteristics, particularly under shear loading. Experimental studies at the specimen level have demonstrated that such joints can show significantly different stiffness and strength depending on their orientation relative to the applied load[7]. Moreover, investigations on specimens containing multiple non-rotationally symmetric joints have revealed that joint orientation and rotation can influence the overall load-bearing capacity and deformation behavior of the structure[8].

Despite these advances, a detailed understanding of how non-rotationally symmetric clinch joints interact with surrounding component geometries is still limited. In real components, joints are embedded within complex structural features such as stiffeners, flanges, and profiles, where load transfer mechanisms are governed not only by joint properties but also by local and global deformation modes of the component. Neglecting this interaction may lead to inaccurate predictions of structural performance and suboptimal joint placement during the design phase.

Against this background, the present study aims to numerically investigate the interaction between a non-rotationally symmetric clinch joint and its surrounding component structure using finite element simulations. A simplified joint modeling approach is employed to efficiently represent the essential mechanical characteristics of the joint while enabling systematic parametric studies. A hat shaped profile joined by such clinch joints is analyzed under three-point bending. The test evaluates the influence of joint orientation on the global load-bearing behavior and deformation response of the component. Furthermore, geometric variations of the hat shaped profile are introduced to assess their effect on the global load bearing response.

The study is expected to show that both joint orientation and component geometry play a significant role in governing global structural behavior as well as local joint response. By investigating these interactions, the work contributes to a better understanding of direction dependent clinch joints at the component level. It also provides valuable insights for the design, orientation, and placement of non-rotationally symmetric clinch joints in real engineering structures.

Methodology

Clinched joints with non-rotationally symmetric geometries exhibit direction dependent mechanical behavior due to their asymmetric load-bearing characteristics. Reuleaux triangle based clinched joints provide a manufacturable joint geometry that introduces pronounced anisotropic in-plane properties while remaining compatible with conventional clinching tools. Previous experimental investigations demonstrated that the asymmetric distribution of neck thickness and interlock around the joint circumference leads to orientation dependent stiffness and energy absorption behavior under shear and bending-dominated loading[7]. These characteristics form the basis for the numerical modelling approach adopted in the present study. The orientation dependent behavior of the Reuleaux triangular clinched joint was first examined at the joint and specimen scale in prior studies[7], [8]. These studies demonstrated that the orientation of individual joints influences load sharing between joints, deformation patterns of the connected sheets, and stress redistribution in the surrounding material. Even for specimens with a limited number of joints, joint orientation effects were shown to affect the global mechanical response. These specimen scale findings provide motivation for the present work. It extends the investigation to a structural scale to assess whether joint orientation effects remain relevant in larger, bending dominated assemblies. (see Fig.1).

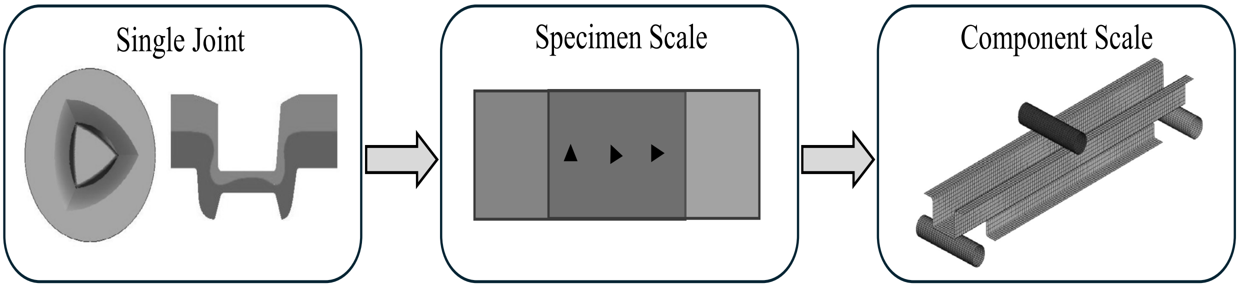

Fig. 1. Schematic overview of the investigation workflow from single joint to structural component.

The present study is exclusively numerical. No experimental testing is conducted within this work. Instead, experimentally derived joint characteristics from previous investigations are used as input data for the numerical joint model. The objective is to evaluate the influence of joint orientation on the global and local response of a joined structure subjected to bending loads. By adopting a purely numerical approach, the effect of joint orientation can be isolated in a controlled manner while enabling the investigation of multiple structural and joint configuration variants. The investigated structure is inspired by a previously published three-point bending configuration used to study the bending behavior of joined sheet metal components[9]. To ensure numerical efficiency, the original concept was simplified by removing the covering plates for hat profiles while the main hat profiles are not used as it is. The structure consists of two hat shaped sheet metal profiles connected by multiple clinched joints located at predefined positions. A three-point bending load case is applied by supporting the structure at two outer points and imposing a prescribed vertical displacement at a central loading point. High-fidelity finite element models of clinched joints based on solid elements can accurately capture local stress states and failure mechanisms, but their high computational cost limits their applicability in large-scale structural simulations involving multiple joints. To enable efficient structural level analyses, a simplified joint replacement modelling strategy is adopted in this study. The joint is represented using the *CONSTRAINED_SPR2 formulation in LS-DYNA, which models the connection as point connector between shell elements, as schematically illustrated in Fig. 2. The connector parameters are calibrated using experimental force displacement data obtained from previous joint and specimen scale investigations. The connector parameters are calibrated using experimentally obtained normal and shear force displacement responses from joint- and specimen-level tests, while other loading modes are not considered in the calibration procedure. In structural bending simulations, however, the joints may experience combined deformation states. Consequently, although the calibrated connector reliably reproduces force transfer trends under dominant normal and shear loading, quantitative accuracy outside these calibrated loading conditions cannot be strictly guaranteed. The resultant force response of the connector as a function of relative displacement reproduces the experimentally observed joint behavior for specific loading directions and joint orientations. The *CONSTRAINED_SPR2 connector formulation computes joint forces based on elastic-plastic force displacement relations with optional softening behavior. However, the formulation does not explicitly represent physical fracture mechanisms of the joint. The model is intended to capture the global mechanical contribution of the joint with minimal computational cost, enabling its application in structural simulations.

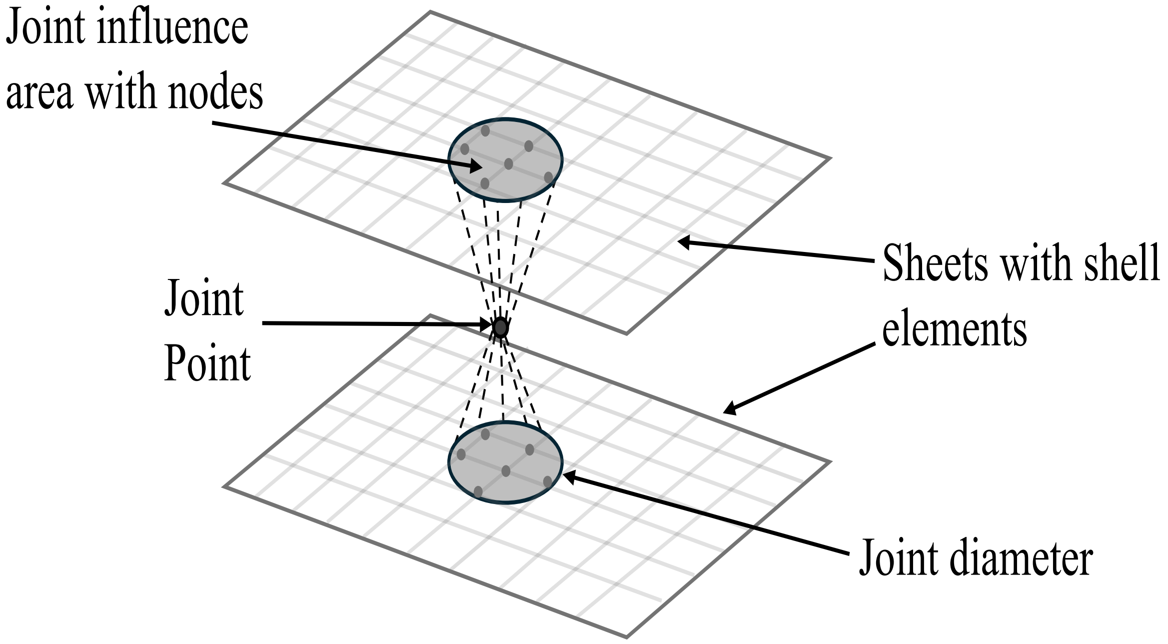

Fig. 2. Point-connector representation of the clinched joint using *CONSTRAINED_SPR2.*

A parametric study is conducted to investigate the influence of joint orientation and structural geometry on the bending response of the structure. A total of ten clinched joints are distributed equidistantly along the lower hat profile. The center-to-center joint spacing, denoted as $\mathbf{d_1}$, is varied between 35 mm and 40 mm, while the height of the lower hat profile, denoted as $\mathbf{b_2}$, is varied between 11 mm and 22 mm. In addition to these global geometric parameters, the joint orientation is treated as a local parameter, with all joints aligned either at 0° or at 180° with respect to the in-plane reference direction. The structure is subjected to a three-point bending load case. The structural geometry, joint locations, and parameter definitions ($\mathbf{d_1}$, $\mathbf{b_2}$) are shown in Fig. 3.

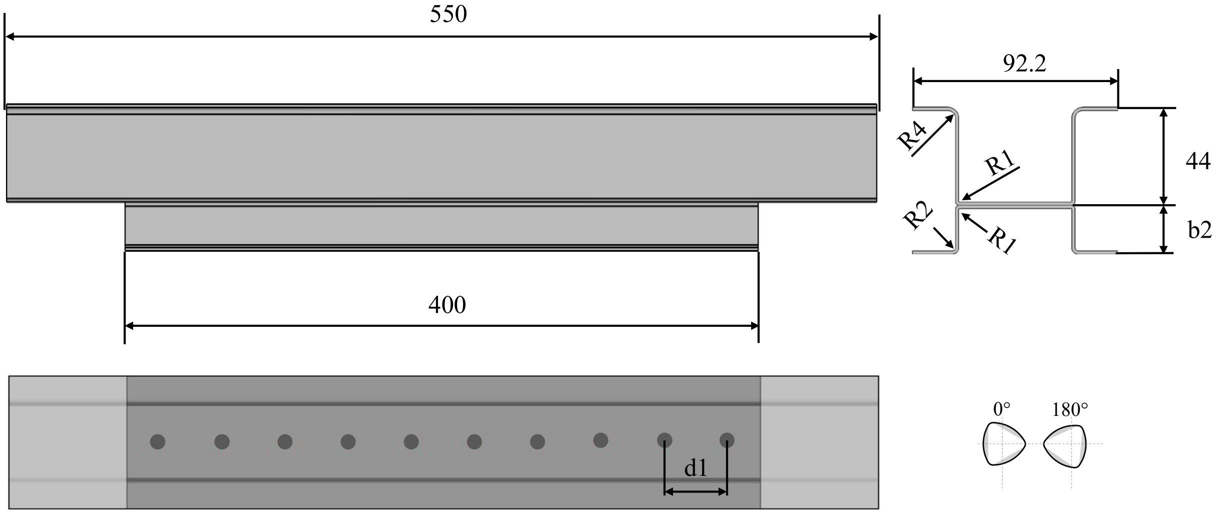

Fig. 3. Geometry and dimensions of the structural model used for the three-point bending simulations (dimensions in mm) and the joint orientations.

Finite Element Modelling

The numerical simulations are performed using the explicit solver of LS-DYNA (ls-dyna_smp_d_R14.0). The finite element model of the investigated structure, including the three-point bending setup, joint locations, supports, and impactor, is shown in Fig. 4. The impactor is positioned with a lateral offset of 5 mm from the geometric center of the structure. The structural components are discretized using fully integrated shell elements (ELFORM 16) with a constant shell thickness of 2 mm and five through thickness integration points. A nominal element size of 5 mm is used, corresponding to a standard mesh resolution commonly applied in full vehicle simulations. Locally refined meshes are employed in regions with geometric bends to ensure adequate mesh quality and deformation representation. The selected mesh resolution represents a compromise between numerical accuracy and computational efficiency and is consistent with mesh densities commonly used in full vehicle simulations. The sheet material is modelled using a Tabulated Johnson Cook material formulation with an experimentally derived plasticity curve. The material corresponds to aluminium alloy EN AW-6014-T4 and is applied consistently to all deformable sheet components. The supports and impactor are modelled as rigid bodies to avoid local deformation effects. Clinched joints are represented using the *CONSTRAINED_SPR2 point connector formulation. Identical connector parameters are assigned to all joints, while two joint orientation variants (0° and 180°) are implemented using separate *CONSTRAINED_SPR2 definitions corresponding to the respective joint configurations, without modifying the surrounding mesh or boundary conditions. The connector parameters are obtained from a calibration procedure based on experimental force displacement data from joint and specimen scale tests. A comparison between the experimental responses and the calibrated connector behavior is shown in Fig. 5. The interactions between sheet components are modelled using an automatic surface-to-surface contact formulation. Sheet-to-sheet contact is activated throughout the simulations to prevent interpenetration during deformation. The structure is subjected to a three-point bending load case. The supports are modelled as rigid bodies constrained in all translational and rotational degrees of freedom. The impactor is modelled as a prescribed rigid body with translational freedom only in the loading direction. A prescribed displacement corresponding to a total impactor travel of 30 mm is applied over a simulation time of 1.2 s. The simulations are conducted without mass scaling, and the loading rate is selected to ensure stable numerical behavior. Although a tabulated Johnson–Cook material formulation is used, strain-rate effects are not explicitly evaluated. The global structural response is evaluated using the force displacement behavior at the impactor, while local response quantities are obtained by extracting the resultant forces transmitted through the individual *CONSTRAINED_SPR2 joint connectors.

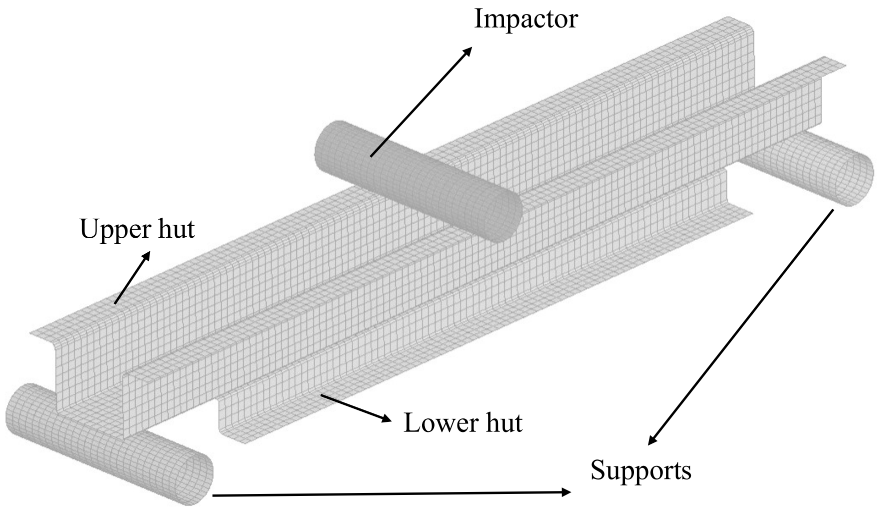

Fig. 4. Finite element model setup of the structure and three-point bending configuration.

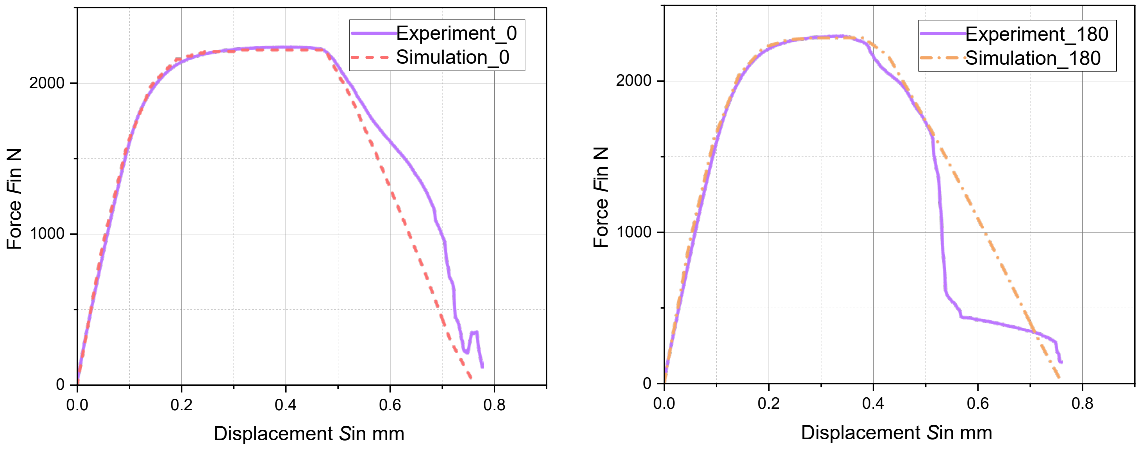

Fig. 5. Calibration of the *CONSTRAINED_SPR2 joint model based on experimental force–displacement data.

Results and Discussion

Global Bending Response of the Structure

The global bending response of the structure is evaluated using the force–displacement behavior at the impactor, as shown in Fig. 6. The results are compared for different combinations of joint spacing and joint orientation, denoted as D40_J0, D40_J180, D35_J0, and D35_J180, where D35 and D40 represent joint spacings of 35 mm and 40 mm, respectively, while J0 and J180 denote joint orientations of 0° and 180°. Up to an impactor displacement of approximately 20 mm, all configurations exhibit nearly identical force–displacement behavior. In this displacement range, the force increases monotonically to approximately 6–7 kN with only minor differences between variants. This indicates that the response is primarily governed by the global bending stiffness of the structure and contact interactions between components, while the influence of joint orientation and spacing remains negligible. In this regime, the joints mainly act as kinematic constraints, and orientation-dependent joint behavior does not yet control the global response. Beyond an impactor displacement of approximately 20 mm, a clear divergence between the curves becomes evident. In this deformation regime, load transfer through the joints becomes progressively more significant, and the structural response increasingly depends on the joint configuration. Differences observed at larger displacements can therefore be attributed primarily to orientation-dependent joint behavior rather than to global structural nonlinearities alone. Both joint orientation and joint spacing influence the transmitted force and the evolution of stiffness degradation. Among the investigated configurations, D35_J180 exhibits the highest load-carrying capacity up to an impactor displacement of approximately 25 mm, indicating a comparatively stiff global response. However, this variant also shows a pronounced and abrupt force reduction beyond this displacement level. In contrast, the remaining configurations (D35_J0, D40_J0, and D40_J180) exhibit a more gradual reduction in force, with the onset of stiffness degradation occurring earlier. This behavior suggests a trade-off between load-carrying capacity and post-peak stability at the structural level. While the D35_J180 configuration sustains higher forces over a larger displacement range, it also experiences a rapid reduction in force once a critical deformation level is reached, whereas the other configurations display a smoother transition into the post-peak regime, indicating a more progressive redistribution of load within the structure. Overall, the results demonstrate that orientation-dependent joint effects remain latent during the early, component-dominated bending phase but become increasingly significant at larger deformations, where joint behavior governs load transfer. These findings extend earlier specimen-scale observations to the structural level and confirm that the orientation of non-rotationally symmetric clinched joints can influence not only the maximum load capacity but also the stability and evolution of the force displacement response in bending-dominated assemblies.

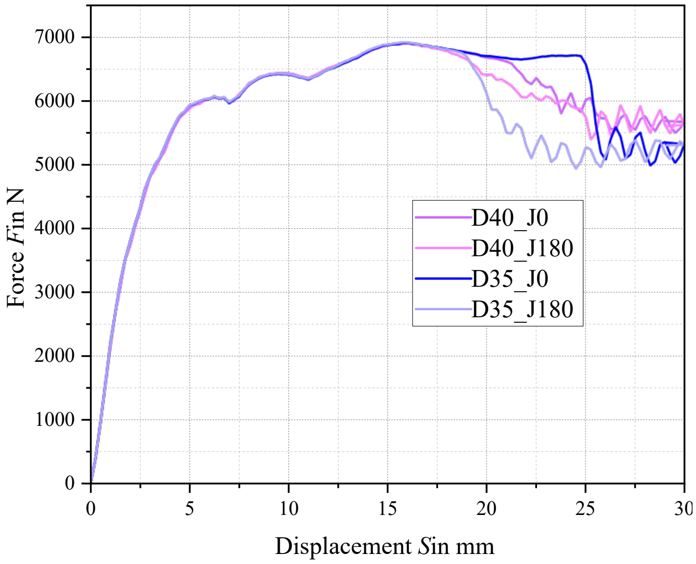

Fig. 6. Global force–displacement response of the structure for different joint configurations. D35 and D40 denote joint spacings of 35 mm and 40 mm, respectively, while J0 and J180 represent joint orientations of 0° and 180°.

Influence of Lower Hat Profile Height on Global Response

The influence of the lower hat profile height on the global bending response is evaluated by comparing configurations with profile heights $b_2 = 11$ mm and $b_2 = 22$ mm, each investigated for both joint orientations (J0 and J180). The corresponding force–displacement responses are shown in Fig. 7, where the notations b22_J0, b22_J180, b11_J0, and b11_J180 are used. A pronounced influence of the profile height on the global response is observed over the entire displacement range. Increasing the lower hat profile height from $b_2 = 11$ mm to $b_2 = 22$ mm leads to a significantly less stiff structural response, as evidenced by the higher force levels attained for comparable displacements. This behavior is consistent with the increased bending stiffness associated with the larger section height and indicates that the global response is strongly governed by structural geometry. Despite this dominant geometric effect, the influence of joint orientation remains clearly visible. For both profile heights, differences between the J0 and J180 configurations emerge beyond the initial deformation phase. Similar to the observations made for the joint spacing study, the force displacement curves for different orientations are nearly identical at small displacements, indicating a component dominated response. With increasing displacement, orientation-dependent differences become more pronounced, demonstrating that joint behavior increasingly contributes to the global response as deformation progresses. For the $b_2 = 22$ mm configurations, the global response is characterized by a higher load-carrying capacity but also by a more abrupt loss of stiffness at larger displacements, particularly for the b22_J0 configuration, which exhibits a pronounced force drop. In contrast, the b_2 = 11 mm configurations show lower peak forces but a comparatively smoother post-peak behavior, with a more gradual reduction in force. This indicates that while increasing the profile height changes global stiffness and load capacity, it may also lead to a less progressive redistribution of load once critical deformation levels are reached. The consistent presence of orientation-dependent effects for both profile heights demonstrates that the influence of joint orientation does not vanish when the global stiffness of the structure is significantly altered. Instead, joint orientation and structural geometry interact, affecting not only the magnitude of the global force response but also the stability and evolution of the force displacement behavior in the post peak regime.

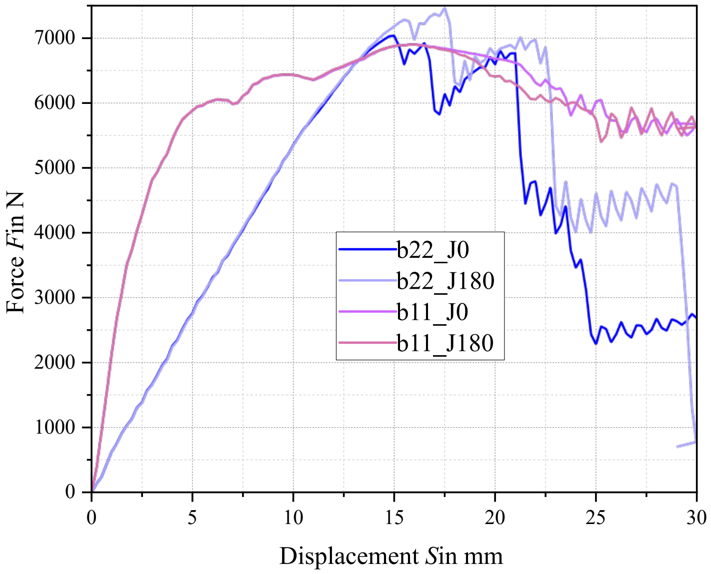

Fig. 7. Global force–displacement response for different lower hat profile heights and joint orientations. b11 and b22 denote profile heights of 11 mm and 22 mm, respectively, while J0 and J180 represent joint orientations of 0° and 180°.

Local Joint Shear Force Response and Load Redistribution

To investigate the origin of the observed differences in global structural response, the local shear forces transmitted through the clinched joints are analyzed. The evaluation focuses on the first four joints along the lower hat profile, as the remaining joints exhibit similar trends and including all ten joints would not provide additional insight. This selection allows a clear assessment of load redistribution while avoiding redundant information. Fig. 8 shows the shear force displacement response of the first four joints for the 0° joint orientation (Fig. 8(a)) and the 180° joint orientation (Fig. 8(b)). For both orientations, the joints initially exhibit a similar increase in shear force, indicating a relatively uniform load sharing during the early stages of deformation. This behavior is consistent with the component-dominated response observed in the global force displacement curves. With increasing displacement, a redistribution of shear forces among the joints becomes apparent. In the 0° orientation (Fig. 8(a)), the shear forces are more unevenly distributed, with certain joints reaching higher force levels earlier than others. This indicates that the load transfer becomes increasingly localized as deformation progresses, leading to a progressive concentration of shear force in specific joints. In contrast, the 180° orientation (Fig. 8(b)) exhibits a more gradual redistribution of shear forces among the analyzed joints. The shear force curves show a more balanced progression, with peak forces occurring at larger displacements and with less abrupt changes compared to the 0° configuration. This suggests that the joint orientation influences the manner in which shear loads are shared and redistributed along the joint line. At larger displacements, a reduction in shear force is observed for individual joints in both configurations, corresponding to the degradation of global stiffness seen in the force displacement response. Notably, the more abrupt force drop observed in some global configurations is reflected at the joint level by a rapid decrease in shear force in one or more joints, whereas configurations with a smoother global response show a more progressive reduction in joint forces. Although the simulations are performed using the explicit solver, the loading rate is selected to approximate quasi-static bending conditions. Quasi-static behavior is verified by monitoring the ratio of kinetic to internal energy throughout the simulation, where the kinetic energy remains negligible compared to the internal energy over the entire loading duration. This indicates that inertial effects are minimal and that the structural response is governed primarily by deformation rather than dynamic effects. Consequently, strain-rate effects are not explicitly evaluated, and the results are interpreted in terms of comparative structural response trends.

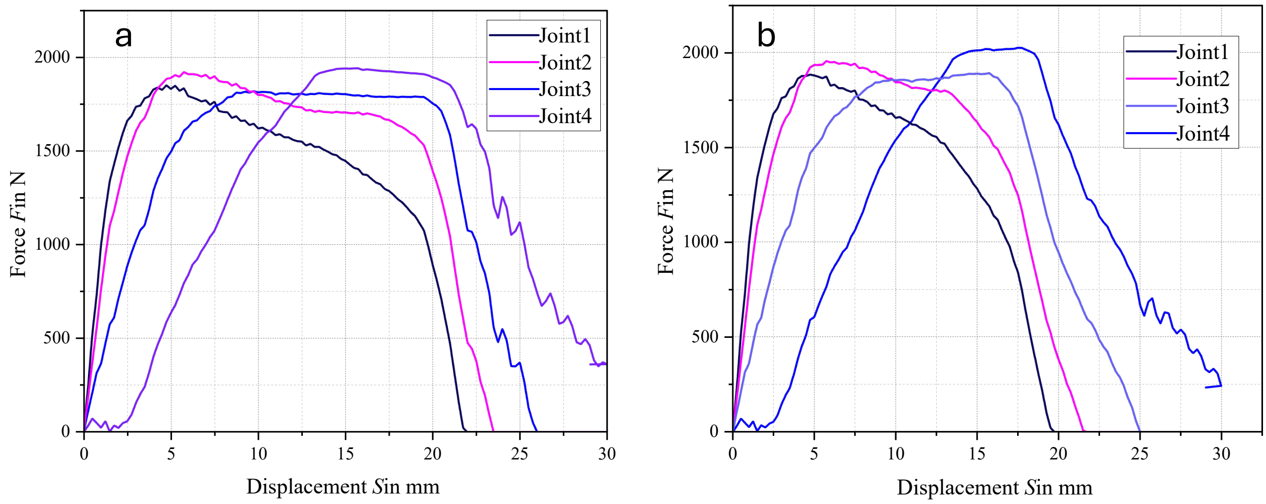

Fig. 8. Shear force–displacement response of the first four clinched joints for (a) 0° joint orientation and (b) 180° joint orientation.

Overall, the joint-level shear force analysis demonstrates that joint orientation affects not only the magnitude of local forces but also the stability of load sharing among joints. These findings provide a mechanistic explanation for the differences observed in the global bending response and confirm that orientation-dependent joint behavior governs load redistribution at the structural level.

Conclusion

Clinched joints with non-rotationally symmetric geometries exhibit orientation dependent mechanical behavior that is often neglected in structural simulations. In this work, the influence of joint orientation on the bending response of a joined structure was investigated using a simplified, joint model calibrated from previously obtained experimental data. The numerical results demonstrate that joint orientation has a negligible influence during the initial, component-dominated deformation phase but becomes increasingly significant at larger displacements, where load transfer through the joints governs the global response. Differences in joint orientation led to measurable variations in global force displacement behavior, including changes in load bearing capacity, stiffness degradation, and post-peak stability. These effects are comparable in magnitude to those induced by changes in joint spacing and structural geometry. Local joint force analyses revealed that joint orientation affects load redistribution among individual joints, influencing both the magnitude and the progression of shear forces along the joint line. Configurations exhibiting higher global load capacity were associated with more pronounced load concentration and less progressive redistribution, while other configurations showed a smoother redistribution of joint forces and a more gradual global response. The findings confirm that orientation-dependent joint behavior observed at joint and specimen scale remains relevant at the structural level. Joint orientation can therefore be considered an additional design parameter in structures assembled using non-rotationally symmetric clinched joints. As the present study is based solely on numerical simulations, the results should be interpreted as modelling-based trends rather than quantitatively validated predictions. Experimental verification at the component level is therefore required to confirm the observed structural effects. Nevertheless, the adopted modelling strategy provides a computationally efficient framework for incorporating orientation-dependent joint behavior into large-scale structural simulations. Future work will focus on component-level experimental validation and on extending the approach to mixed joint orientations and additional loading conditions.

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References

[1] M. Merklein, M. Jäckisch, C. M. Kuball, D. Römisch, S. Wiesenmayer, and S. Wituschek, "Mechanical joining of high-strength multi-material systems − trends and innovations," *Mechanics & Industry*, vol. 24, p. 16, 2023, doi: 10.1051/MECA/2023013.

[2] P. Groche, S. Wohletz, M. Brenneis, C. Pabst, and F. Resch, "Joining by forming-A review on joint mechanisms, applications and future trends," *J. Mater. Process. Technol.*, vol. 214, no. 10, pp. 1972–1994, Oct. 2014, doi: 10.1016/J.JMATPROTEC.2013.12.022.

[3] L. Kaščák, E. Spišák, and J. Mucha, "Clinchrivet as an alternative method to resistance spot welding," *Acta Mechanica et Automatica*, vol. 7, no. 2, pp. 79–82, 2013, doi: 10.2478/AMA-2013-0014.

[4] X. Gao, C. Chen, X. Ren, and H. Peng, "Experimental investigation on the mechanical square clinching process for joining Al5052 sheets," *Proc. Inst. Mech. Eng. B J. Eng. Manuf.*, vol. 237, no. 5, pp. 791–800, Apr. 2023, doi: 10.1177/09544054221112750;WEBSITE:WEBSITE:SAGE;JOURNAL:JOURNAL:PIBB; WGROUP:STRING:PUBLICATION.

[5] X. Ran, C. Chen, H. Zhang, and Y. Ouyang, "Investigation of the clinching process with rectangle punch," *Thin-Walled Structures*, vol. 166, p. 108034, Sep. 2021, doi: 10.1016/J.TWS.2021.108034.

[6] X. Gao, C. Chen, X. Ren, and Y. Li, "Investigation on failure mechanism of the square clinched joints with different sheet thicknesses," *Eng. Fail. Anal.*, vol. 134, p. 106013, Apr. 2022, doi: 10.1016/J.ENGFAILANAL.2021.106013.

[7] C. Steinfelder, C. Acksteiner, and A. Brosius, "A new joint with versatile properties based on a Reuleaux triangle geometry," *CIRP Annals*, vol. 74, no. 1, pp. 405–409, Jan. 2025, doi: 10.1016/J.CIRP.2025.03.002.

[8] D. R. Devulapally, C. Steinfelder, T. Tröster, and A. Brosius, "Impact of non-rotationally symmetric joint orientation on neighbouring joints and component performance in lap shear specimens," *MATEC Web of Conferences*, vol. 408, p. 01035, 2025, doi: 10.1051/MATECCONF/202540801035.

[9] M. Reil, D. Morin, M. Langseth, and O. Knoll, "A novel tests set-up for validation of connector models subjected to static and impact loadings," *Int. J. Impact Eng.*, vol. 158, p. 103978, Dec. 2021, doi: 10.1016/J.IJIMPENG.2021.103978.