

Non-rotationally symmetric joints – Mechanisms and load bearing capacity

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Abstract. Traditionally, joints are cylindrical and rotationally symmetric. In the present study, non-rotationally symmetric joints are used for joining steel and Glass mat-reinforced thermoplastic sheets (GMT). In addition, the study also analyzes the impact of non-rotational symmetric joint rotation on the load-bearing capacity. Single lap joint specimens were fabricated using the In-Mold assembly technique for joining steel sheets with GMT. Tensile shear tests were performed on different orientations of the joint geometry, and it was observed that changing the joint orientation influences the load-bearing capacity. The joints are constitutively modeled using beam elements and the influence of joint rotation on load distribution is examined through a static simulation study.

Introduction

The joining of manufactured components presents a significant hurdle in any industry, especially in the case of automobile body construction, where thousands of joints are made using different joining processes. Reducing or optimizing the joints according to loading conditions can reduce the number of joints, saving many resources[1]. Due to their ease of joining, most joints are typically rotationally symmetric; nevertheless, using these traditional joints might reduce the degree of design freedom. Non-rotationally symmetric joints can have an additional degree of freedom by changing the orientation of the joint geometry in a specific direction. Since they are rotationally non-symmetric, they have good torsional resistance and instead of using two rotationally symmetric joints one non-rotationally symmetric joint can be used. This helps in reducing the number of joints which also helps in saving production time.

The knowledge of load distribution and the type of loads acting on joints is adequately understood because of the complexity of loading. In most cases, the joints are either designed with a higher factor of safety or their number is increased, which increases the cost, weight, and time. The study conducted by [2] on joint loading in global bending and torsion in an automotive body in white (BIW) shows that most of the joints are shear-loaded. This is because more than 70% of the joints are lap joints. The following study conducted by [3] on loading the BIW with different real-life maneuvers also shows that joints are mainly shear-loaded and suggests a strong potential for joints with non-rotationally symmetric geometry.

In addition, substantial work on the load distribution among joints with rotationally symmetric geometry exists in the literature [4]. According to this study, when arranged in a line, the load distribution among the joints is uneven; the joints near the edges take most of the load, comparatively less load. The investigation by [5] on load transfer in multi-spot ultrasonic welded joints in thermoplastic composites also confirms the uneven load distribution among the joints in a line. Furthermore, the study conducted by [6] on load transfer in multi-fastener joints of metal



and composite laminates suggests that joints with increased stiffness can carry more loads than others and help in even load distribution in a line. It was also suggested that increasing the diameter of the bolts in the middle of the configuration can help in the even distribution of loads because of the increase in stiffness with increasing the bolt geometry. The present study investigates the effect of non-rotationally symmetric joints and changing the joints' orientation on even load distribution. The current investigation focused on non-rotationally symmetric joints produced from a combination of steel and GMT, specifically designed in an elliptical shape. The joints were arranged in three orientations by changing their orientation angles. The effect of orientation on joint stiffness and load-bearing capacity was investigated, and the impact of the locking mechanism of the joint was also in focus. Joints with and without interlocking and failure mechanisms of joint combinations were examined by considering tensile shear test properties as well. At the end of the study, preliminary numerical studies were carried out with joints in an array, and the load distribution was analyzed. Moreover, it was also considered whether changes in the orientation of joints affect the load distribution among other joints.

Method

Tensile shear specimens are produced by joining steel sheets with fiber composite material using a non-rotationally symmetric form-fit joint. The joining process consists of a two-step operation. In the first step, the two joining members to be joined are prepared. Hole flanging is employed to prepare the steel sheet, followed by cutting the GMT into the necessary dimensions and subsequently heating it in the oven. In the second step, both the joining members are stacked upon each other in a heated mold and pressed together. Different variations of the joint are produced by rotating the joint geometry. The joints were subjected to shear testing via a universal testing machine, and the load vs displacement data were analyzed to observe the bearing capacity of the joints.

Materials.

The thermoplastic composite material used in this study is a chopped fiberglass mat reinforced thermoplastic (GMT) with randomly oriented glass fibers in a mineral-filled polypropylene (PP) matrix. It is commercially known as S153A248-M1 and is procured from Mitsubishi Chemical Advanced Materials Composites AG with a glass fiber content of 52%. The sheet metal used is HCT590X (1.0941), a dual-phase steel with remarkably high tensile strength and good cold-forming capacity. The material is zinc-coated and procured from Salzgitter Flachstahl GmbH. The properties of both materials are tabulated in Table 1. Laser cutting is used for preparing sheet metal parts, offering high precision and good cutting surface quality. The dimensions of the laser-cut specimens can be seen in Fig. 1.

Hole-Flanging.

Hole-flanging, or collar drawing, is a tension-compression metal forming technique described in the German norm DIN 8584. A punch-and-die setup with a punch holder is used for forming flanges around holes in sheet metal components. The blank with a 20 mm diameter hole is clamped by a blank holder and is pushed into the drawing die by a rigid punch, which forms a flange in the shape of the die around the hole. This process is used extensively in the automotive industry for lightweight applications [8]. In the present study, elliptical hole flanges are formed in the sheet metal component and are used to examine the joining of metal with GMT. The flange acts as an anchor and can bear load in the joint. Flanges were produced in three orientations (0°, 45°, and 90°) and were investigated in the current study. The process is schematically represented in Fig. 2 below.

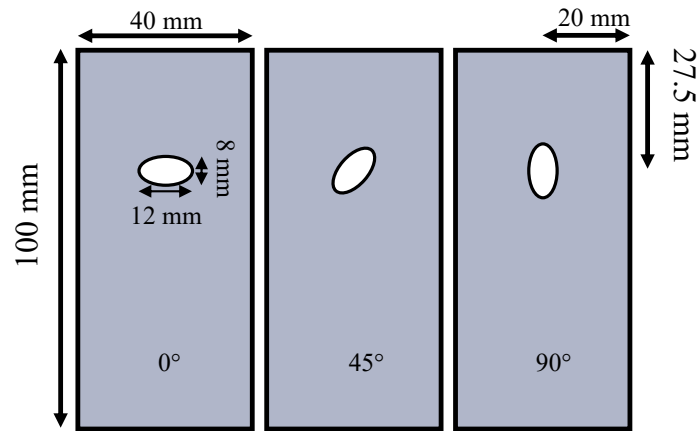


Figure. 1 Laser-cut sheet metal with dimensions in three orientations.

Table 1. Material details

Material	Thickness [mm]	Tensile strength [MPa]	Young's modulus [GPa]	Density [g/cm ³]
HCT590X- Steel	1.5	590	210	7.85
S153A248-M1-Composite	4.8	145	86	1.40

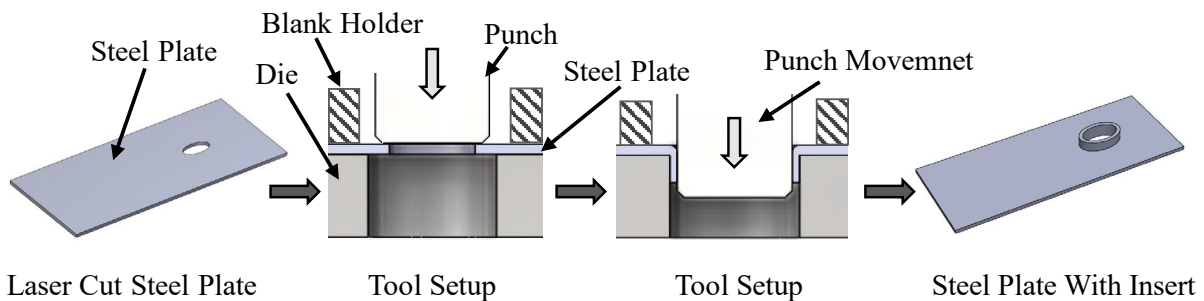


Figure. 2 Process of sheet metal hole-flanging process.

In mold assembly.

The two materials were joined by In-Mold Assembly (IMA) of hybrid components using compressive molding [9]. GMT laminate is cut into the required dimensions by a plate shear and is heated in the convection oven for 10 mins at 250°C. Steel specimen with a hole flange is inserted into the molding tool, which is maintained at 100°C; the hot GMT specimens are then immediately transferred and stacked onto the metal specimen, which is pressed via a mechanical press (Synchropress 1M-300). Higher compressive forces, combined with good flowable properties of the GMT material, ensure that the material is uniformly distributed and ideally takes the shape of the mold. The process flow of the joining method is shown schematically in Fig. 3. Two laminates are stacked one upon the other to increase the thickness and strength of the composite part. During the compressive molding process, the heated thermoplastic composite material flows into the flange, forming a secured joint. The fiber flow and the interlock can be observed by a cut-section

view of the specimen in Fig. 5. The dimensions of the lap shear specimen and the process flow are described in Fig. 4. In the experimental investigations conducted, two types of flanges were utilized: one without edge interlocking and the other with interlocking. The influence of interlocking, joint fracture, and load-bearing capability in various orientations are investigated and compared.

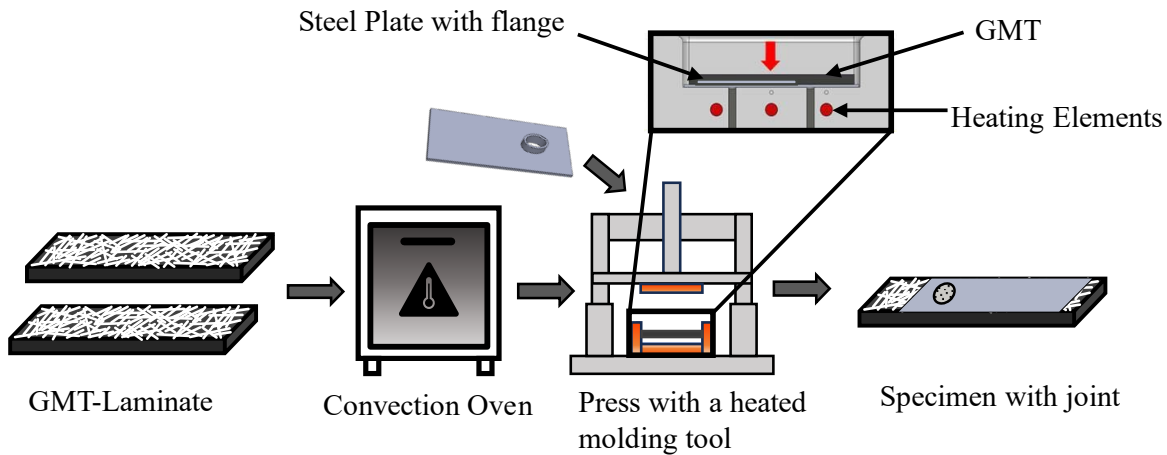


Figure. 3 Process of joining through in mold assembly through compressive molding.

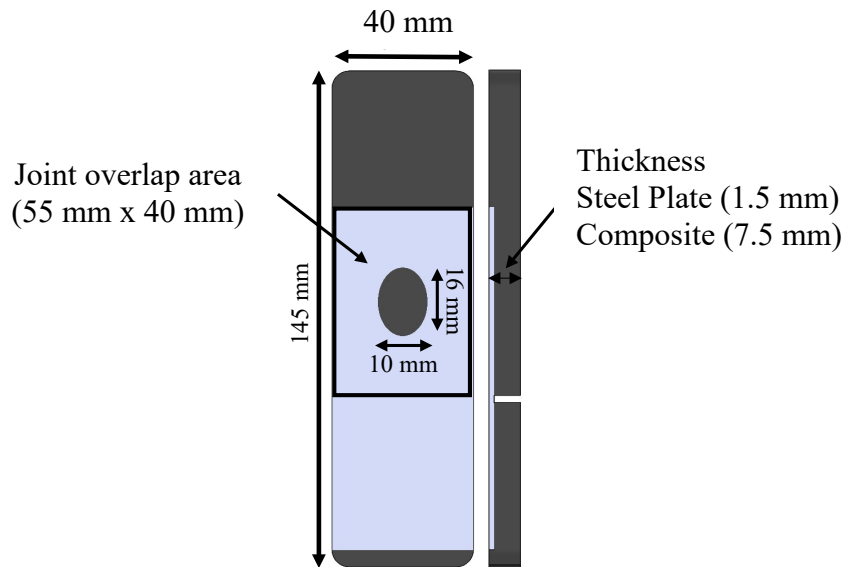


Figure. 4 Joined specimen with dimensions.



Figure. 5 Cut section of specimens A) Specimen without edge interlock. B) Specimen with edge interlock.

Finite Element Simulation

The finite element simulation comprises two steps. In the first step, the joint stiffness derived from experimental data is utilized to calibrate individual joints. Subsequently, in the second phase, calibrated single joints with various orientation angles are employed to simulate multiple joints arranged in a line. For the simulation, an implicit solver of the Software Ansys LSDYNA and

Hyper mesh preprocessing software is used for meshing. The model is created by considering the dimensions of the joint overlap area in the experiments. In the calibration phase, only the overlap of two joining members is considered and is simulated. The two joining members are represented by fully integrated shell elements (elform=16), and thickness values are given as the thickness of steel and GMT. The joint is modeled using discrete beams (beam formulation=6) with a beam length equal to the total thickness of the joint. Discrete beam elements are 1-D elements with six degrees of freedom generally used for representing and calibrating joints and fasteners. This beam element has a local coordinate system (r, s, t); the two beam nodes connecting the two shell members are aligned along the r-direction. The third node of the beam can be aligned in s or t-direction according to the direction of stiffness (see Fig. 7). Beam elements are connected to the shell members using the constrained nodal rigid body (CNRB) constraint. Fig. 6 shows the FE model with a single joint. The steel member is subjected to full constraint, while the composite member experiences a prescribed displacement of 0.4 mm in the x-direction over a duration of 8.04 seconds, as indicated by experimental observations.

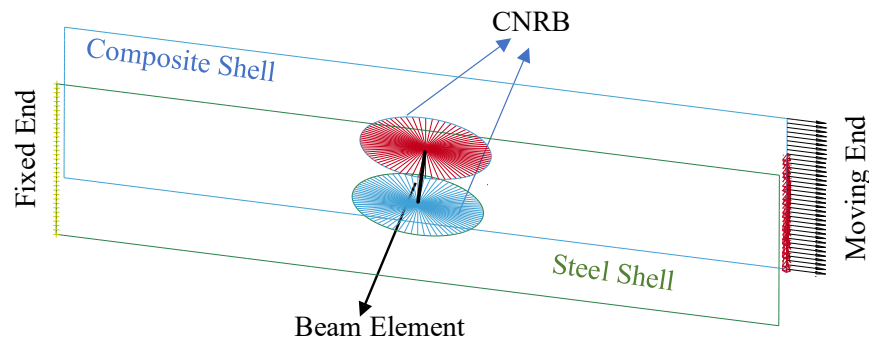


Figure. 6 FE Model setup for single joint calibration

The stiffness values are calculated regarding the experimental results by linear curve fitting in Origin pro software. The stiffness values are defined as an input in the material data card of the discrete beam element *MAT_LINEAR_ELASTIC DISCRETE BEAM. The material data of the joining members are also obtained from the material data sheets and implemented in the simulation using the *MAT_ELASTIC card. More information about the mentioned keywords can be found in the LS-DYNA keyword user’s manual [10].

Contact definition between the joining members is represented using the contact card *AUTOMATIC_SURFACE_TO_SURFACE_MORTAR. The composite member is considered master, and the steel member is determined as an enslaved person with a coefficient of static friction value of 0.1. Since no pull-out tension tests are experimentally conducted, a normal stiffness value of 10000 N/mm is defined as a constant value in the calibration of joints. The average stiffness values for three different joint rotations can be seen in the following Table 3. Since no rotation takes place during testing, the rotational degree of freedom is restricted in all three directions. All the joints were calibrated for a displacement of 0.4 mm and a time of 8.04 seconds, which was taken from the experimental results, and the same conditions are also used for simulating multijoint setup.

Table 3 Stiffness values for different joint orientation

Rotation Angle	Average Stiffness [N/mm]	Standard Deviation
0°	11550	142.94
45°	11300	294.90
90°	12000	893.81

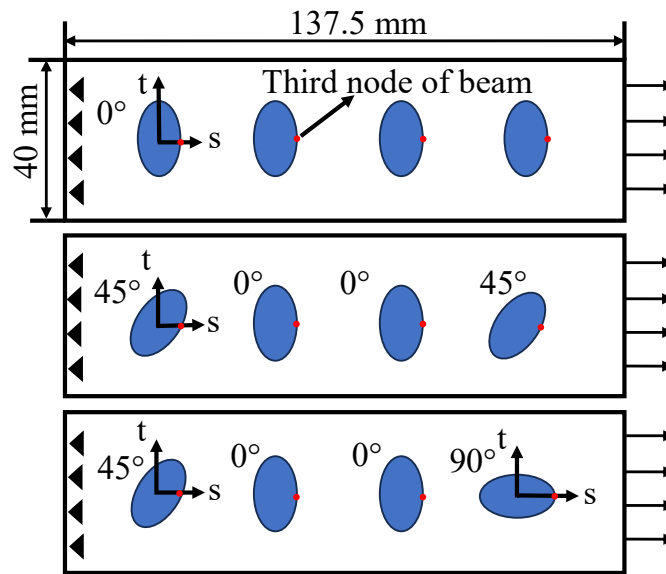


Figure.7 FE model with multi-joint setup

Results and discussion

The non-rotationally symmetric joint specimens were tested for lap shear strength using the universal testing machine MTS Criterion C45 with a testing speed of 3 mm/s. For each orientation of the joint, three tests were conducted to reduce the errors and abnormal results. The steel member of the specimen is fixed, and the composite part is stretched. All the specimens were tested until failure, and the load vs displacement data was acquired using the integrated load cell in the testing machine. Fig. 8 shows the stages of the specimen during the testing. Fig. 9 compares the load vs displacement data for three orientations. The linear part of the graph represents the elastic region. After this stage, plastic deformation occurs, and the joint tends to rotate because of the secondary bending. The two joining members separate as the specimen is further stretched, reducing the joint's load-bearing capacity. It can be observed that a change in the joint's rotation significantly affects the maximum load-bearing capacity of the joint. Joints with 45° orientation bear the most negligible load, and joints with 0° orientation show maximum load-bearing capacity. The peak load-bearing capacity of the joints is given in Table 4 below. One more critical observation from the graph is the displacement value at which the maximum load is seen. Joints with 0° orientation show maximum load at a displacement value, which is more than the other two orientations. From this, it can be concluded that a change in orientation affects not only the load-bearing capacity but also the displacement at which the joint is bearing the maximum load. The following Fig.10 presents a comparison of joints with and without edge interlocking. It can be noticed that the joints with interlock perform noticeably lower compared to those without interlocking. The reason for this might be because of the length of the metal flange in the composite member. Since only a small portion of the metal flange is in the composite member, joints with interlock were fractured early, thus reducing the maximum load-bearing capacity.

Table 4 Maximum load with change in joint orientation

Orientation angle	Maximum load [N] (Without interlock)	Maximum load [N] (With interlock)
0°	7959.56	7033.04
45°	5972.35	5843.82
90°	7216.25	5833.39

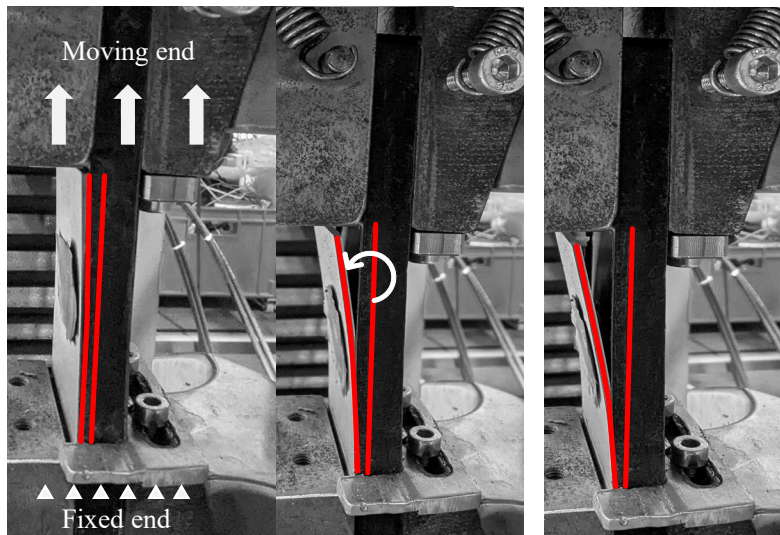


Figure. 8 Secondary bending of the metal plate during shear testing

The load distribution study is conducted using the calibrated values obtained from the single-joint setup and is subsequently applied to a configuration comprising four joints arranged in a line. First, all the joints with similar rotation are considered and are simulated in the load distribution study. Given that these joints are calibrated primarily based on stiffness, the load distribution study does not reveal any noticeable distinction in even load distribution, as there are minimal fluctuations in stiffness values. The reason for uneven load distribution is still not known but it might be the cause of using different thicknesses of joining members. Fig. 11 shows that the initial joint bears most of the load, while the subsequent joints carry comparatively lesser loads. In addition, several joint orientation combinations were studied to evaluate possible differences in the load distribution. Since there is no large difference in stiffness between different orientations a large change in load distribution has not been observed. Making use of this finding, the method of modifying stiffness values to provide the best possible load distribution across joints is investigated. It was found that a decrease in the first two joints' stiffness combined with an increase in the last two joints' stiffness had advantageous results for load distribution (see Fig. 11). Joints with similar orientation angles are only examined for stiffness optimization study, the additional freedom of changing the joint orientation adds one more degree of freedom in this case. This shows that the usage of joints with different stiffness can help distribute the load evenly in multi-joint setups. Further investigations into the impact of alterations in the size and geometry of non-rotationally symmetric joints on stiffness would advance our understanding. Moreover, examining the influence of inter-joint distances would provide additional insights.

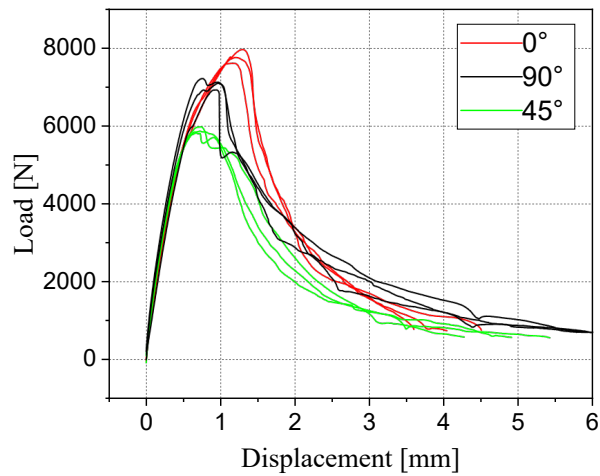


Figure. 9 Load vs. displacement graph for three orientations without the interlock.

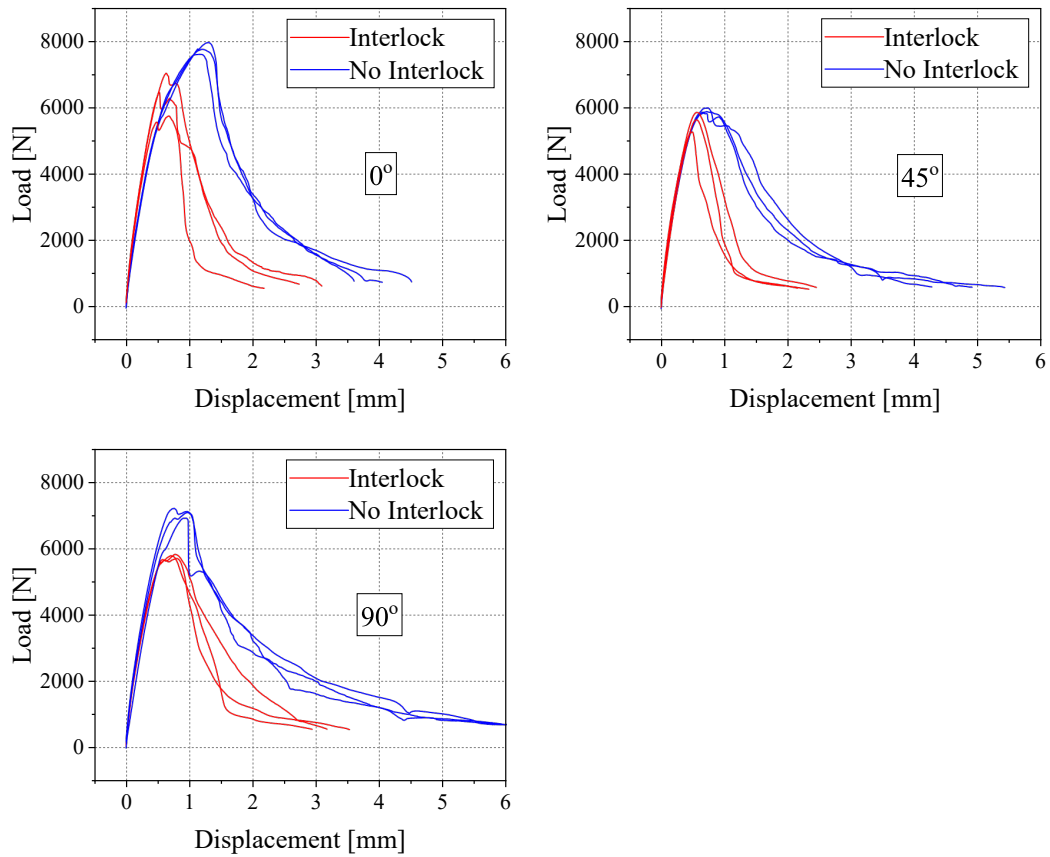


Figure. 10 Comparison of load vs displacement graph for three orientations

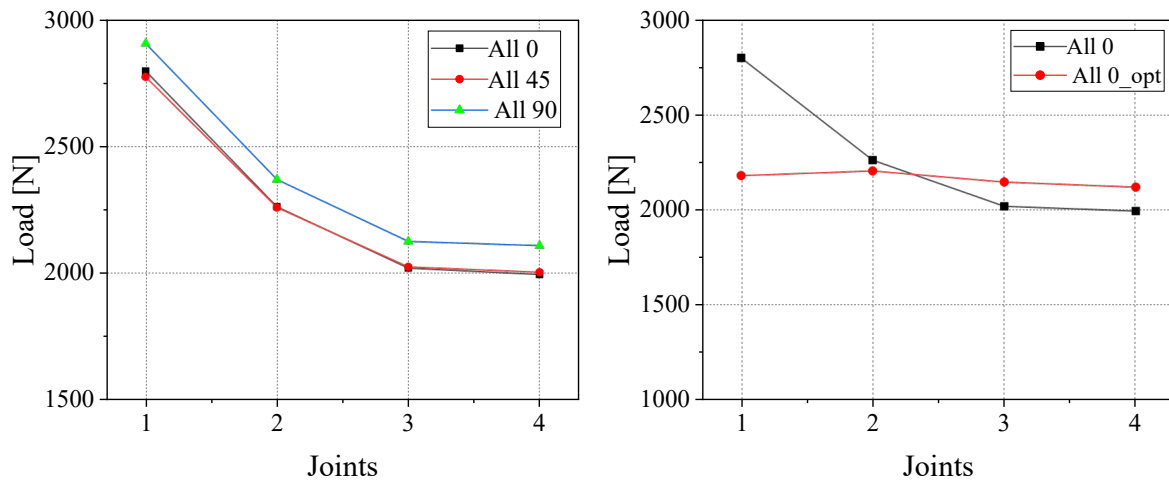


Figure. 11 Load distribution in multi-joint setup using non-rotationally symmetric joints. All 0 corresponds to all joints oriented in 0 orientation and All 0_opt corresponds to joints with optimized stiffness.

Conclusion

Non-rotationally symmetric joints were used to join steel and composite materials utilizing the In-Mold assembly technique. The joints were made with and without interlock configuration and tested for load-bearing efficiency—joints with interlocking mechanisms performed remarkably lower than those without one. Changing the orientation angle of the joints affects the maximum load-bearing characteristics. It was observed that joints with 0° orientations show higher load-bearing capacity in comparison to other orientations. The load distribution study by arranging multiple joints in a line shows the need for stiffer joints in even load distribution. Further experimental investigations on multi-joint setups using non-rotationally symmetric joints and changing the joints' shape and inter-joint distance can help understand these joints better.

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