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FASTENERLESS JOINING OF CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITE TO ALUMINUM.

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ABSTRACT

Continuous efforts are underway for the reduction of the structural weight of transit through the introduction of a multi-material metal-composites system. There are major challenges in joining dissimilar materials to result in optimum structural integrity. The conventional joining techniques have limitations in terms of preparation time, weight penalty resulting from adhesives, and uncertainty in joint integrity. Recently adoption of macro scale mechanical interlocking in the adhesive joining resulted in significant improvement of joint performance. This made mechanical interlocking gain an attention for hybrid joining. In this study, fastenerless method of mechanical interlocking based on Japanese wood joining craft is considered for joining carbon fiber-reinforced polyamide thermoplastic composite to aluminum. Different interlocking joining designs (IJDs) were developed. The joints were obtained by force-fitting the male into the female counterpart. Here the male and female segments joined at macro level with no joining integrity at the interface. Further, these joints were tested and evaluated for tensile strength. A finite element analysis (FEA) model is developed for stress analysis and studying failure mechanisms of the IJDs. It was observed that the geometry of IJD dictates the failure mode and material composition governs the maximum strength achieved by a particular IJD. Each IJD showed higher load capacity with metal as a female counterpart to the composite compared to other way round.

Keywords: Multi-material, lightweight, fastenerless, mechanical interlocking, interlocking joining designs

1. INTRODUCTION

Automobile manufacturers continue to seek avenues for lightweighting conventional and battery vehicles. Material combinations resulting in a hybrid structure are a promising approach for lightweighting [1]. Hybrid multi-material structures not only provide the benefit of lightweighting but also results in reduction of cost, and improvement in safety resulting in the overall optimization of the body. The joining of dissimilar materials such as metals with polymers, fiber reinforced composites, or sometimes ceramics is a key element of hybrid structure(s). Carbon fiber reinforced polymer (CF) composite is gaining attention for lightweighting vehicles due to excellent mechanical properties, high impact tolerance and energy absorption capabilities, fatigue resistance, and thermal stability [2]. Researchers have attempted various joining approaches to join the CF composite to aluminum due to their high strength-to-weight ratio.

Mechanical joining is widely used for joining different components. In many instances, fasteners such as bolts, screws, and rivets are used as shown in Figure 1. These provide ease in assembling and disassembling the components for example for component replacement, repair, and/or inspection. However, the major drawback of mechanical joining technique is the drilling of a hole, which increases local stress concentration. Holes, notches, steps, etc. result in loss of strength in fiber reinforced composites due to debonding/delamination. Moreover, the use of bolts and rivets adds weight to the structure and adversely affects lightweighting.

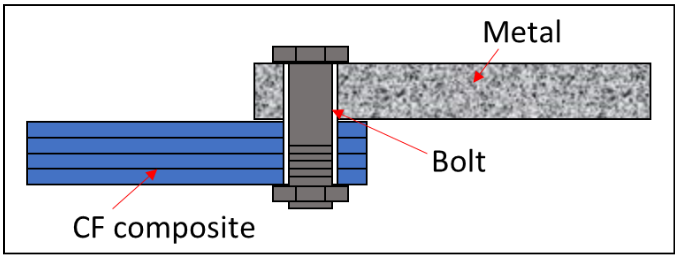


Figure 1: Mechanical joining of carbon fiber reinforced polymer composite to metal using bolt.

In adhesive joining, the adhesive is placed and pressed between the adherends to realize the joint. The advantage of it over conventional mechanical joining is the even distribution of stresses over the joint area. Adhesive joining is attractive to provide corrosion resistance, design flexibility, high damage tolerance, and supports lightweighting. Despite all these benefits it suffers from drawbacks such as surface pretreatment of joining components, long curing time of the adhesive, low joint strength, and susceptibility to weathering.

Researchers are investigating the impact of macro level interlocking features on the hybrid joint performance [3]. O'Brien et al. conducted a systematic study of effect of introduction of macro level mechanical interlock on the adherend surface in adhesive joining of metal [4]. It resulted in the significant improvements of up to 27% and 542% are obtained in joint failure load and work to failure, respectively. This improvement in the performance attributed to the additional impedance provided by interlocking feature to relative adherend displacement. It prevented the adhesive to attain its failure strain without plastic deformation of the adherends. In other words, the joint strength is not just dependent upon the quality of adhesive bond, rather relies on the plastic deformation of aluminum which resulted in enhancement of failure load. Karthik et al. extended this study to adhesive joining of CF composite and aluminum and reported a 10% and 75-120% increment in lap shear strength and work to failure respectively as compared to the adhesive joint without any features [5]. Moreover, this kind of joining showed high energy absorption capacity indicating its usefulness in the enhancement of the crashworthiness performance of a vehicle.

In this study, novel mechanical interlocking joining of carbon fiber reinforced polyamide thermoplastic composite to aluminum 6061 is evaluated. This method of joining is motivated by the Japanese techniques of woodcraft [6]. IJDs shown in Figure 2 were designed using SolidWorks 2023 (Dassault Système's). The design parameters of these IJDs are discussed in the subsequent sections. Fastnerless joining enables minimum alteration to the load path(s) resulting in the load bearing by interlocked moiety. These joints were tested under quasi-static loading for evaluating their load bearing capacity. It was further extended to understand the influence of material composition on the joint strength by interchanging the material for male and female sections of the joint.

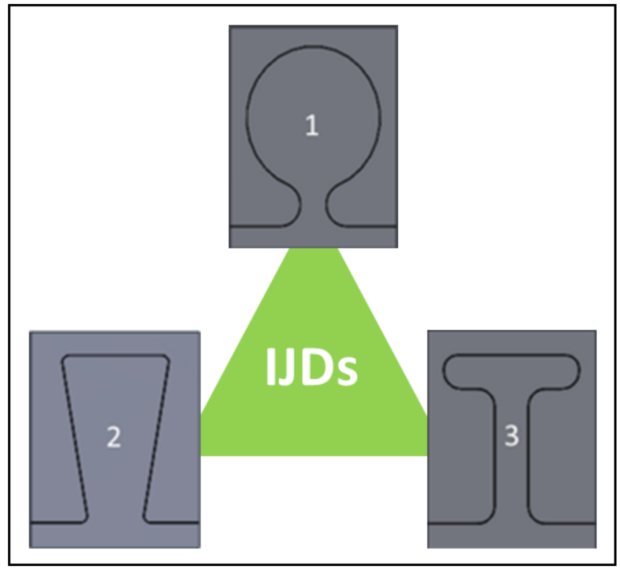


Figure 2: Various mechanical interlocking joint designs including 1. IJD – 1, 2. IJD – 2, and 3. IJD – 3.

2. MATERIALS AND METHODS

Six (6) mm carbon long fiber thermoplastic (LFT) composite plate was manufactured using polyamide 6 with 30% by weight carbon fiber (CF30PA6) LFT pellets supplied by PlastiComp, Inc., Minnesota, USA, by extrusion compression molding [7]. The aluminum 6061 plates of 6 mm thickness were procured from McMaster-Carr, USA [8]. The samples were machined to 100 x 25 mm dimension for both composite and aluminum via waterjet cutting as shown in Figure 3. For each design, five specimens were prepared for tensile testing. The tensile testing was performed on a 50kN Test Resources Frame, Test Resources, Minnesota, USA, with a displacement control rate of 2 mm/min. The influence of the respective materials as 'male' or 'female' section(s) of the joint was investigated by testing the joint in both configurations namely Comp - M and Comp – F. Comp – M represents the composition where composite act as a male and aluminum act as a female whereas Comp – F represents the configuration vice-versa.

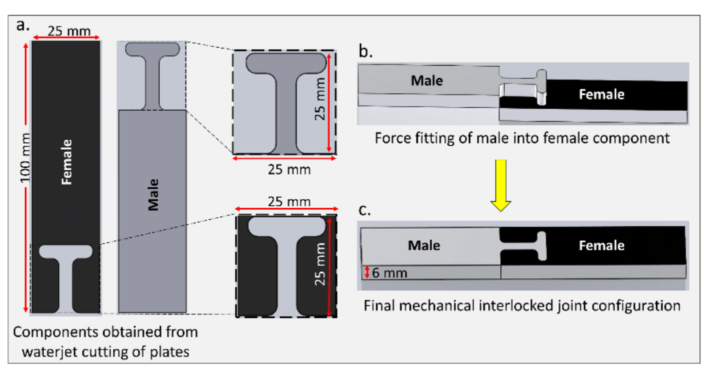
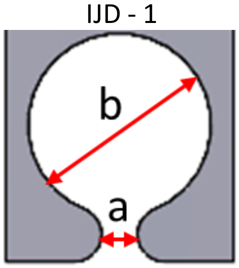
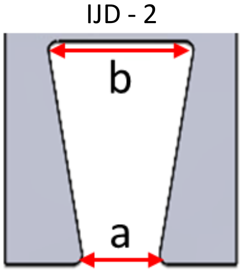
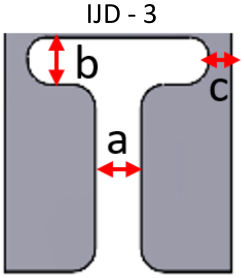


Figure 3: Schematic of mechanical interlocking joint process. a. The samples after waterjet cutting operation, b. The male segment was force fitted to the female counterpart of the joint, c. Resultant joint.

2.1 Design parameters for IJDs:

The main constraint on the IJD is that it should not exceed the 25 mm x 25 mm joining area. This is a standard practice followed for evaluation of adhesive bonding by joining the 25 mm x 25 mm adherend area [9]. Initially, simple designs were developed with two degrees of freedom as shown in Table 1. The IJD-1 is derived from a jigsaw puzzle whereas IJD-2 is based on a dovetail joint, primarily used in the joining of wood. Further, IJD-3 is designed with three degrees of freedom. Configuration IJD3 is inspired from the flange of an I-beam. The idea here is that the horizontal section (flange) will act as a hook/anchor to provide mechanical interlocking to the joint.

Table 1: Various IJDs with their design parameters. The design parameters shown is from the samples tested experimentally. These optimum parameters were obtained based on the design constraint.

IJD	Parameters
IJD - 1 	a = 5 mm b = 20 mm
IJD - 2 	a = 7 mm b = 14 mm
IJD - 3 	a = 5 mm b = 5 mm c = 2.5 mm

3. RESULTS AND DISCUSSION

3.1 Effect of interlocking geometry on joint strength:

In this study, the basic joint designs including IJD-1, IJD-2, and IJD-3 were tested to evaluate the influence of interlocking design on the joint strength using Comp – M configuration. Hereafter the strength of a joint refers to the maximum load borne by the joint structure.

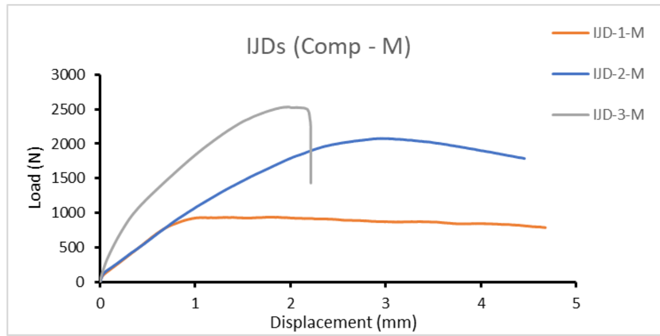


Figure 4: Load displacement curves for IJDs in Comp – M composition. The response of IJD-1-M, IJD-2-M, and IJD-3-M represented in the orange, blue, and grey colors respectively.

Figure 4 shows the load displacement curves of IJDs with Comp – M configuration. The detailed curves for each IJDs can be referred from appendix. The load displacement curve for IJD-1 indicates that the load increases linearly till it reaches the maximum load. Then it subsequently deviates from linearity and attains a plateau where the load value remains almost constant. As the joint specimen gets loaded tangentially the interlocking moiety tightens. The linear response of the load could be result of progressive bending of the female part at the point A as shown in Figure 5. The loss in contact between female and its counterpart at the point A resulted in stagnant load value. This might be the cause for premature failure of IJD-1 (<1000 N). Preliminary analysis based on the observed failure mode suggests that the tensile loading exerts lateral forces on the female part at point A. This could be the reason for the distortion of the joint structure.

For IJD-2, a non-linear load displacement response was recorded. This was attributed to the evolution of complex forces around the male-female interface as shown in figure 6. This includes the frictional force between the CF composite and aluminum 6061 as indicated by the inspection of the failure mode. In subsequent sections, the FEA study illustrates the influence of it on the joint strength. In case of IJD-2, the joint strength was reported around 2100 N, slightly higher than IJD-1.

As the degree of freedom increases the response to the axial loading becomes more complex. For instance, it can be seen from the load displacement behavior of IJD-3. It is comprised of a short linear region and extended non-linearity till failure occurs. As mentioned earlier, the horizontal section (flange) acts like a hook or anchor enabling mechanical interlocking of the joint. Moreover, as depicted in figure 7, it would generate intricate interlocking about the edges as the test proceeds. This is attributed to the complex shape of load displacement curve. The maximum strength observed for IJD-3 was ~ 2500 N the highest of the tested designs.

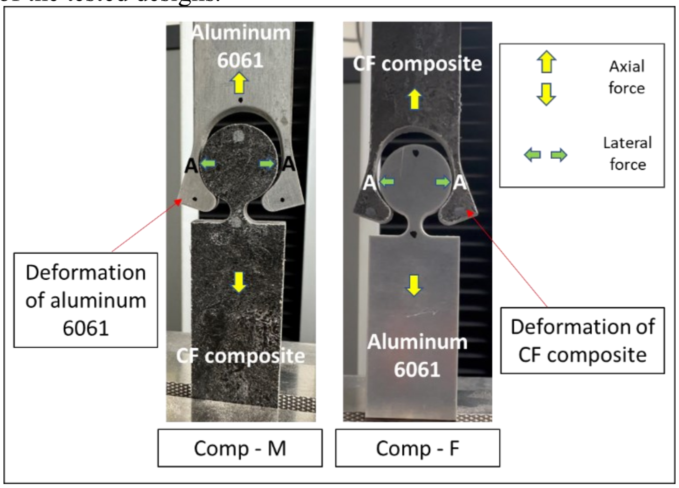


Figure 5: Failure modes of IJD-1 in Comp – M and Comp – F.

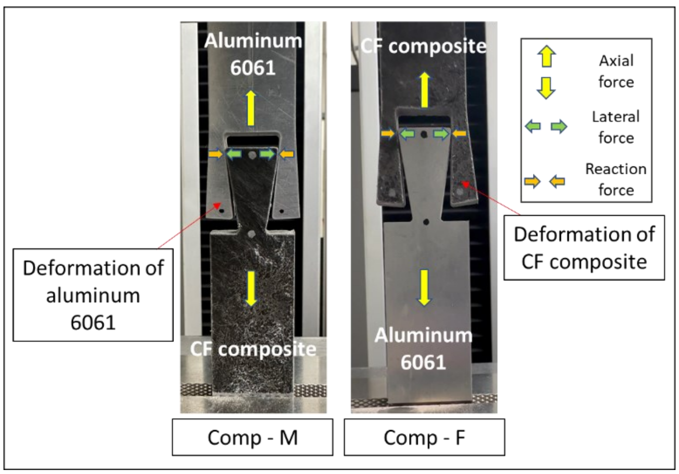


Figure 6: Failure modes of IJD-2 in Comp – M and Comp – F.

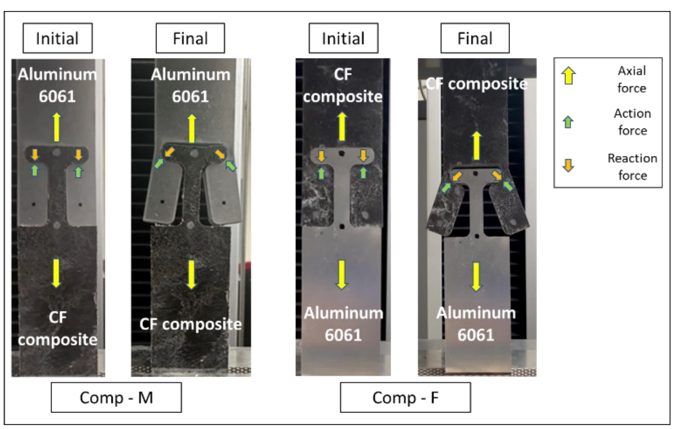


Figure 7: Illustration of the developed forces during tensile testing of the IJD-3 joint.

3.2 Effect of material configuration on joint strength:

Here the joint strength was evaluated for IJD 1 to 3 with Comp – F composition. The test parameters were kept constant as per the Comp - M. The idea behind the testing was to obtain insight into the significance of material property with respect to tensile strength of the joint. Further, this study would be helpful in deciding the optimum material configuration for the particular IJD. Further, it bolsters the importance of pairing the optimal IJD with ideal material composition for obtaining superior joint strength.

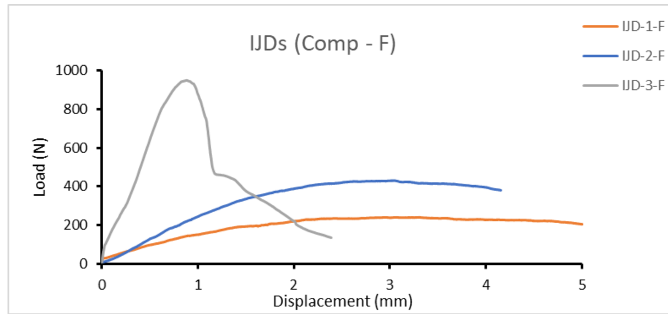


Figure 8: Load displacement curves for IJDs in Comp – F composition. The response of IJD-1-F, IJD-2-F, and IJD-3-F represented in the orange, blue, and grey colors respectively.

The load displacement behaviors for each IJDs with Comp – F are depicted in Figure 8. The load response was non-linear for IJD-1 in the case of Comp – F contrary to Comp – M load displacement curve. The failure occurred with a maximum load below 250 N. Even though a similar failure mode was seen in Comp – M, but still the peak load reported is 76% lower compared to Comp-M. This makes Comp-F the least suitable configuration to consider for IJD-1.

Even though there is no substantial difference between the shape of the load displacement curves of Comp - F and Comp – M in the case of IJD-2, there is significant disparity in terms of the maximum force at failure. It was observed that the peak load drops to 410.5 N (for Comp-F) compared to 2025 N (Comp-M). i.e., reduction of > 75%. However, it can be seen that the failure mode of Comp – F is identical to the Comp – M configuration.

In the case of IJD-3, the load displacement graph of Comp - F distinctly differs from the Comp – M, in terms of the failure mode, but also the maximum load ~ 68% lower for Comp-F. For the instance, the load increases non-linearly until it attains the maximum value and then follows the same non-linearity while dropping gradually, unlike the case of Comp-M where it drops instantly.

Overall, it can be inferred that the Comp – M showed higher joint performance compared to Comp – F. The observation of the failure modes revealed that the female part undergoes higher deformation irrespective of material. The remarkable difference between the joint strength of Comp – M and Comp – F configurations indicates that the material properties does play a significant role in joint strength. To understand its role completely a thorough experimentation is needed along with measurement of local strain/stress analysis. Techniques such as digital image correlation (DIC) need to be coupled during testing.

3.3 Finite element analysis model for various mechanical joint designs:

Finite element analysis (FEA) was conducted to investigate the IJD configurations with a commercially available FE solver, ABAQUS. Structural elements (mesh type=C3D4) are used to perform the analysis. The coefficient of friction (COF) between the composite and aluminum surfaces is calibrated in the simulation. This calibrated value is then used to compare the maximum load for each joint geometry. To simulate the tensile test, we design the boundary condition of the simulation. The bottom of the male part is fixed as a grip part, which had the same length as the grip surface. The upper grip surface of the female part is coupled to a reference point, and the displacement of the reference point is controlled to conduct the tensile test. To measure the loading force, we use the same experimental test setup as the load cell in the test machine to measure the applied load. The coupled force between the specimen surface and the reference point is measured as the loading force. We use the material property values summarized in Table 2 for the FEA simulation [10,11].

Table 2: FEA simulation input parameters.

Material properties	30%CF PA6 LFT	Al 6061
Specific gravity (kg/m^3)	1270	2700
Tensile modulus (GPa)	22.1	68.9
Tensile Strength (MPa)	269	310

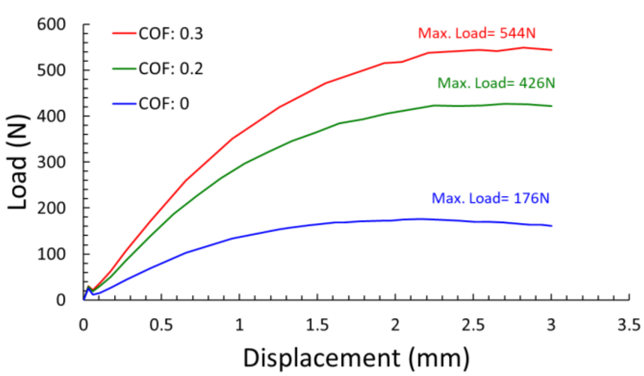


Figure 9: Calibration of coefficient of friction, based on comparison of maximum load.

We calibrate the coefficient of friction (COF) by comparing the maximum load obtained from the simulation and the experiment, as shown in Figure 9. We use the IJD-2 geometry in the simulation because it has the largest contact surface area between the male and female parts. We vary the COF value from 0 to 0.3 and find that the maximum load increases as the COF value increases. The most adjustable maximum load is 544 N when the COF is 0.3, which matches the experimental result of 530 N.

Using the determined COF value, we conduct tensile test simulations with different joint designs and compositions. Figure 10 compares the location of stress concentration for each case. For IJD-1, the stress is concentrated on the female part, which smoothly opens during the test. In IJD-2, stress is concentrated on both the female and male parts due to the tapered design of the male part continuously receiving load when the female part opens. The tapered part prevents the female part from opening. In IJD-3. The male part prevents slip and opening with the T-shape locking, leading to stress development on the female part and the T-shape of the male part. The T-shape design prevents the female parts from slipping and opening, with the male part acting like a hook or anchor imparting a mechanical interlocking effect on the joint. The simulation results are shown in Figure 11, which compares the maximum load for different designs. The tendency of the simulation results shows good agreement with the experimental results. However, as the simulation only includes linear mechanical properties, nonlinear mechanical behavior is not captured in this model. For the future work, we will include nonlinearity to capture a more accurate behavior.

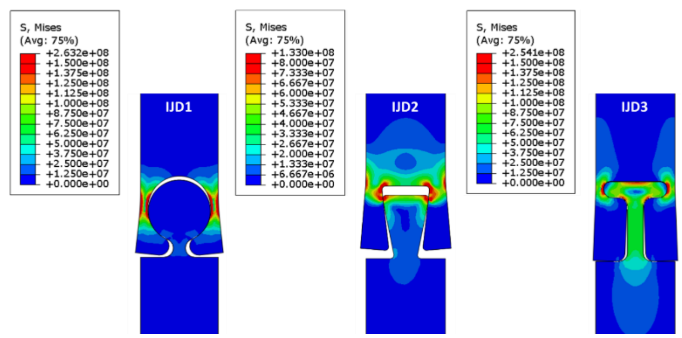


Figure 10: Comparison of stress concentration on the different joint designs.

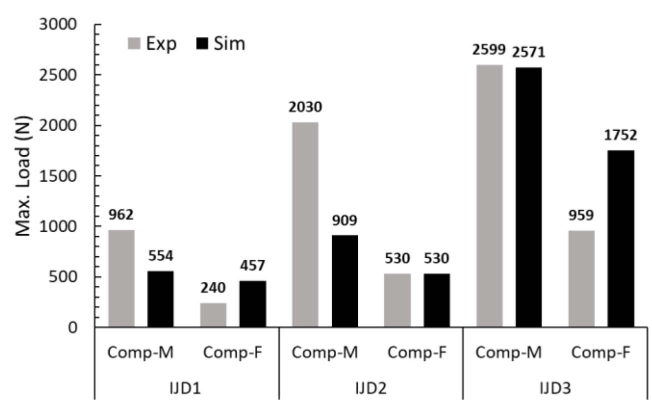


Figure 11: Simulation results for the maximum load with different geometries and compositions.

4. CONCLUSIONS

The fastenerless joining method based on IJDs investigated for joining CF composite with aluminum 6061. The IJD-3 (2500 N in Comp-M and 950 N in Comp-F composition) shown higher joint strength compared to rest of the IJDs. Also, it was noted that the Comp – M composition resulted in optimum joint performance compared to its alternative scenario amongst all the tested IJDs. It showed the role of material properties in governing the strength of the joint with identical IJD. The relationship between IJD and their performance (load displacement curve) could be established by in depth analysis of local strain behavior using techniques like DIC. We designed and verified a FEA model using experimental results. With this FEA model, we were able to capture stress concentration resulting in the tensile test for each IJD, providing deeper insights into the complex mechanical behavior of the joint. Furthermore, the trends of the simulation for predicting the maximum load shows good agreement with the experimental results, suggesting that our FEA model accurately captures the mechanical behavior of the joint. Overall, this study demonstrates good agreement between the experimental and FEA results of fastenerless IJDs.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Naito, J.; Suzuki, R. Multi-Material Automotive Bodies and Dissimilar Joining Technology to Realize Multi-Material. Kobelco Technol. Rev. 2020, No. 38, 32.

[2] Babu, A.; Bhattacharya, A. Review on Use of Carbon Fibre (Reinforced Plastics) in Automotive Sector. J. Crit. Rev. 2020, 7, 679.

[3] Pokkalla, D. K.; Hassen, A. A.; Nuttall, D.; Tsiamis, N.; Rencheck, M. L.; Kumar, V.; Nandwana, P.; Joslin, C. B.; Blanchard, P.; Tamhankar, S. L.; et al. A Novel Additive Manufacturing Compression Overmolding Process for Hybrid Metal Polymer Composite Structures. Addit. Manuf. Lett. 2023, 5, 100128.

[4] O'Brien, M.; Mortell, D. J.; Corbett, M. C.; O'Higgins, R. M.; McCarthy, C. T. Mechanical Performance and Failure Behaviour of Miniature Aluminium Joints with Novel Interlocking Reinforcement. Int. J. Adhes. Adhes. 2019, 95, 102431.

[5] Ramaswamy, K.; O'Higgins, R. M.; Corbett, M. C.; McCarthy, M. A.; McCarthy, C. T. Quasi-Static and Dynamic Performance of Novel Interlocked Hybrid Metal-Composite Joints. Compos. Struct. 2020, 253, 112769.

[6] Sumiyoshi, T.; Matsui, G. Wood Joints in Classical Japanese Architecture. 1991, p 124.

[7] Alwekar, S.; Yeole, P.; Kumar, V.; Hassen, A. A.; Kunc, V.; Vaidya, U. K. Melt Extruded versus Extrusion Compression Molded Glass-Polypropylene Long Fiber Thermoplastic Composites. Compos. Part A Appl. Sci. Manuf. 2021, 144, 106349.

[8] Oversized Multipurpose 6061 Aluminum Sheet 1/4" Thick https://www.mcmaster.com/89155K11/.

[9] Ramaswamy, K.; O'Higgins, R. M.; Lyons, J.; McCarthy, M. A.; McCarthy, C. T. An Evaluation of the Influence of Manufacturing Methods on Interlocked Aluminium-Thermoplastic Composite Joint Performance. Compos. Part A Appl. Sci. Manuf. 2021, 143, 106281.

[10] PlastiComp long fiber reinforced thermoplastic composite (Technical Data Sheet) https://www.plasticomp.com/complet-lcf30-pa6/.

[11] Aerospace Specification Metals https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t (accessed Dec 4, 2023).

Appendix

The spread across the tested specimens can be seen from the tensile testing data for all the tested joint design in both configurations.
Fig. 1, fig. 2, and fig. 3 demonstrates the load displacement curves for Comp – M configuration.

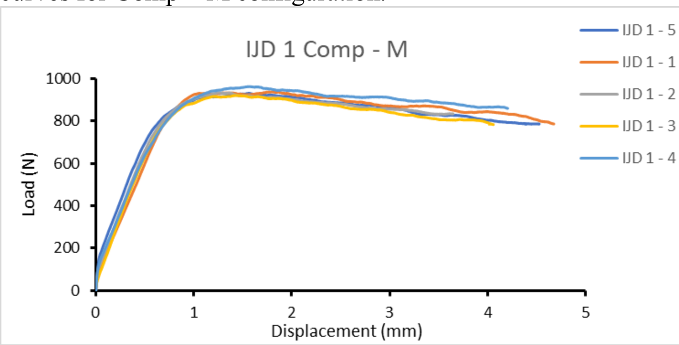

Figure 1: The load vs. displacement curves of IJD – 1 in Comp – M configuration.

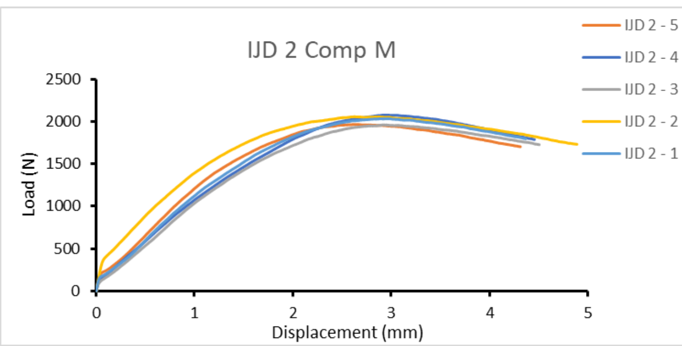

Figure 2: The load vs. displacement curves of IJD – 2 in Comp – M composition.

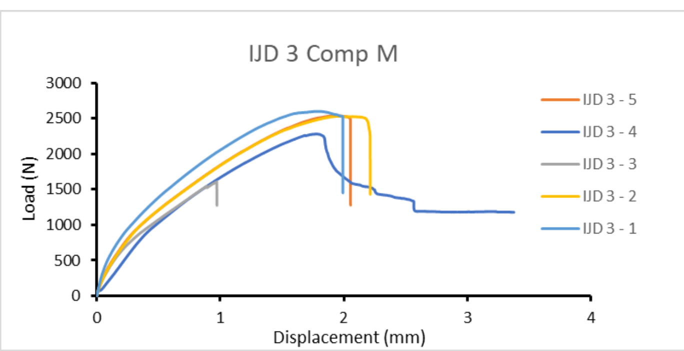

Figure 3: The load vs. displacement curves of IJD – 3 in Comp – M configuration.

Fig. 4, fig. 5, and fig. 6 demonstrates the load displacement curves for Comp – F composition.

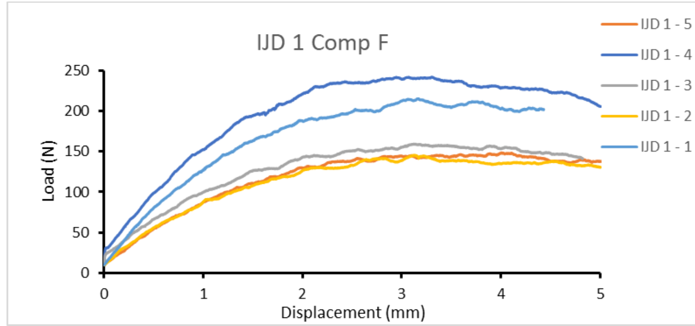

Figure 4: The load vs. displacement curves of IJD – 1 in Comp – F composition.

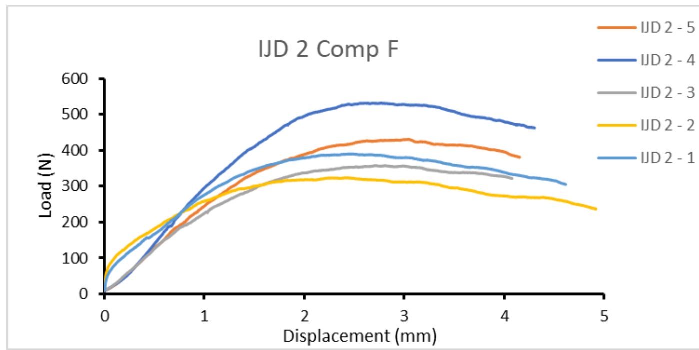

Figure 5: The load vs. displacement curves of IJD – 2 in Comp – F configuration.

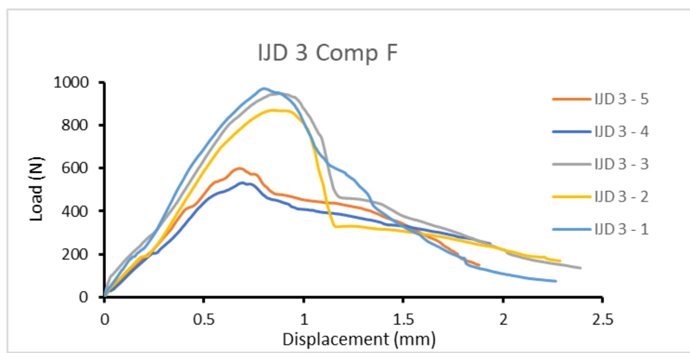

Figure 6: The load vs. displacement curves of IJD – 3 in Comp – F composition.