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ADDITIVELY MANUFACTURED FASTENERS

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Abstract

Additive manufacturing (AM) has reached a critical point which enables production of complex, high resolution, custom parts from robust materials. However, traditional fasteners are still use to join these complex parts together. Integrating fasteners into additively manufactured parts is beneficial for part production but there is uncertainty in their design. To understand how the fasteners fit and function, mechanical property data was collected on the prototypes. This data along with insights gained while building and testing the prototypes increased the knowledge base of design for additive manufacturing and build-to-build variability in selective laser sintering (SLS).

Introduction

Engineers invented additive manufacturing in an attempt to reduce cost and time constraints binding the prototyping process. The project sponsor, Sandia, already benefits from this rapid, inexpensive prototyping in their broad array of research projects. Additive manufacturing (AM) has reached a critical point which enables production of complex, high resolution, custom parts from robust materials. AM also provides a newfound design freedom, allowing design focus to shift from how a part will be made to how a part needs to function. This remarkable shedding of existing design constraints paves the way for innovation of newly designed fasteners. The primary project aim was to develop fasteners that could be integrated into AM parts to alleviate the need for traditional fasteners. Since variability in part properties limits functional use of additively manufactured products, the secondary project aim was to increase Sandia's understanding of build-to-build variability in selective laser sintering (SLS). Data was collected on build-to-build property variability, by building the fasteners in multiple build locations on the same machine over several days.

Concept Generation

Before creating design concepts, background information on SLS was collected to understand the process and its capabilities [1]. Existing design guidelines were used to help the design process, indicating what feature sizes would build successfully [2]. Understanding that there is variation in SLS part properties impacted design decisions attempting to and accommodate variation [3].

Permanent Cap Fastener

Figure 1 shows the initial SolidWorks model of the permanent pin and cap fastener design; the cap is the upper part and the pin is the lower part.

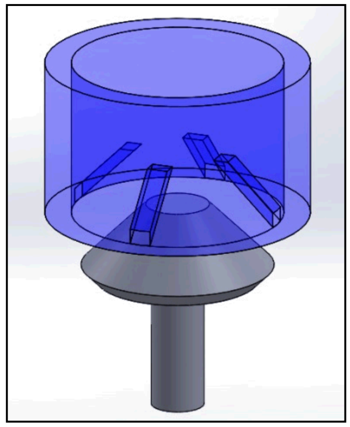

Figure 1. SolidWorks model of permanent cap fastener

The cap contains four cantilevered beams each at 45° from the base that control the pins motion. Once the pin slides into the cap, the pin cannot retract because the beams prohibit motion in that direction. Figures 2 and 3 show cross-sections of the pin and cap in the unfastened and the fastened positions, respectively.

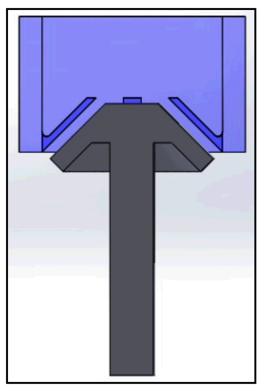

Figure 2. Unfastened permanent pin and cap

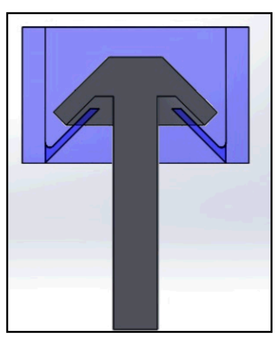

Figure 3. Fastened permanent pin and cap

As seen in Figure 1, the cap is not enclosed at the top to allow for the pin to be used multiple times for experimentation. In the final design, the cap would not be open at the top, making it a permanent fastener.

Reusable Cap Fastener

Since Sandia wanted both permanent and reusable fasteners, a variation of the pin and cap fastener that could be unfastened was designed. To do this, the AM capability of creating interior channels that would lock the pin in place was used. Figures 4 and 5 show SolidWorks models of the reusable pin and cap fastener in the unfastened and fastened positions, respectively.

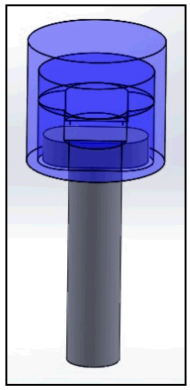

Figure 4. Unfastened reusable pin and cap

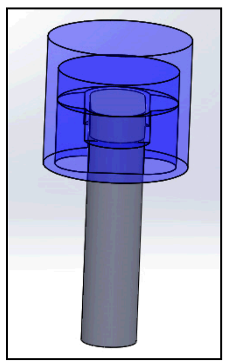

Figure 5. Fastened reusable pin and cap

The cap has multiple layers that the pin navigates before reaching its final fastened position, see the layers in Figure 14.

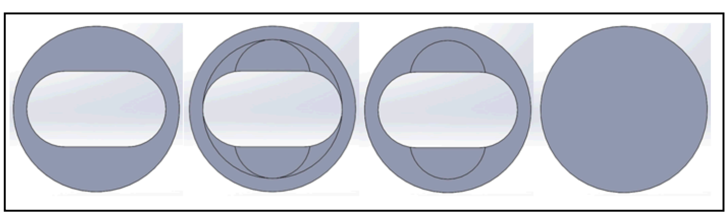

Figure 6. Layers in the reusable cap fastener from bottom (left) to top (right)

The pin inserts the cap through the bottom, or first, layer and moves up to the third layer. In the third layer, the pin can rotate 90° and retract down to the second layer. In the second layer, the pin cannot move while it is in tension. Once the tension is released, the pin can be removed from the cap by reversing the steps taken to fasten it.

Permanent Quatrefoil

Figure 7 shows the initial SolidWorks model of the permanent quatrefoil fastener design; the cap is the upper part and the pin is the lower part in Figure 7.

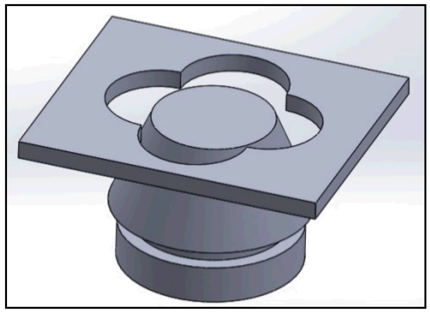

Figure 7. SolidWorks model of the permanent quatrefoil fastener

This cap uses the corners of a quatrefoil as modified cantilever beams, and is inspired by the permanent cap fastener. Figure 8 shows the fastened cap and pin. The groove in the pin is designed to fix the cap in place.

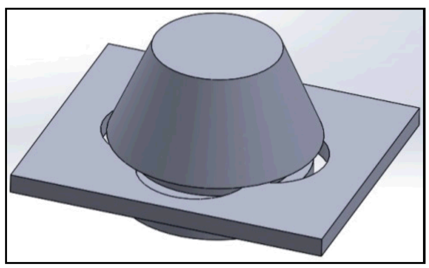

Figure 8. Fastened permanent quatrefoil

Based on order of magnitude information gleaned from SolidWorks deformation studies of other fasteners, these quatrefoil corners were determined to be too thick for elastic deformation necessary to allow the pin to slide into the cap. The cap was therefore modified to allow the corners to function as the ends of four true cantilever beams, as shown in Figure 9.

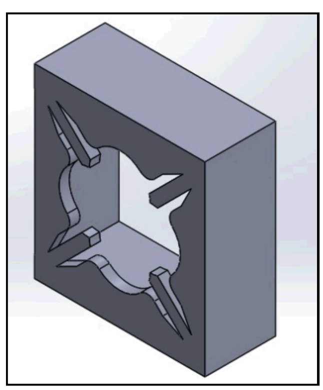

Figure 9. Modified permanent quatrefoil cap

Figure 9 also shows how the edges of the cap were extruded to facilitate a uniform application of force during fit testing.

Guided Icosafoil Fastener

Figure 10 shows the initial SolidWorks model of the guided icosafoil fastener design; in this figure the cap is the upper part and the pin is the lower part.

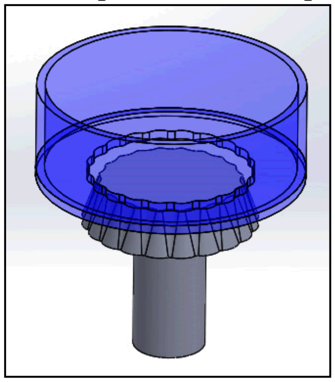

Figure 10. SolidWorks model of guided icosafoil fastener

This fastener builds on the concept explored in the permanent quatrefoil, and its cap intends to use the filleted corners of 20 radially distributed circular arc sections in an icosafoil to mimic the function of cantilevered beams. This fastener further seeks to prevent rotation about the guiding axis of the pin by adding grooves to the pin which match respective grooves in the cap's filleted icosafoil geometry. Figure 11 shows the guided icosafoil fastened.

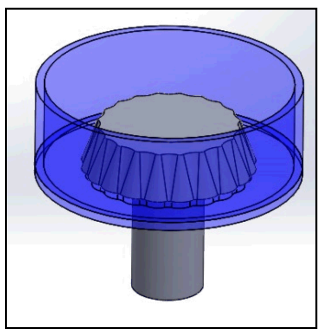

Figure 11. Fastened guided icosafoil

For similar reasons as with the permanent quatrefoil, additional ductility was introduced into the guided icosafoil cap, again by extruding cuts to create a series of miniature cantilever beam structures. Figure 12 presents the final cap for the guided icosafoil fastener.

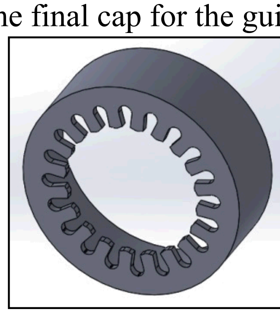

Figure 12. Modified guided icosafoil cap

The ends of the beam structures are still textured to fit in the grooves on the pin, and with added ductility this fastener is more likely to pass the fit test.

Reusable Claw Fastener

Figure 13 shows the initial SolidWorks model of the reusable claw fastener design; in this figure the claw is the lower part and the pin is the upper part.

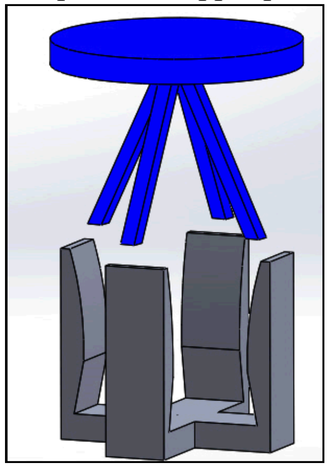

Figure 13. SolidWorks model of reusable claw fastener

This fastener builds on the use of cantilevered beams in order to maximize ductility, and therefore ease of fastening. In this initial design, both the claw and the pin employ cantilever beam structures which should elastically deform and then return to original geometry, interfacing as they fasten. After preliminary design work, it was noticed upon inspection that this fastener would disengage with any rotation of the pin about its vertical axis. In order to alleviate this concern, the cantilever beams of the pin were transformed into a cone, as presented in Figure 14.

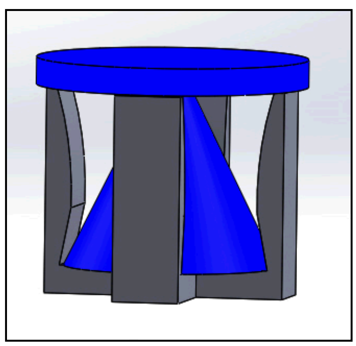

Figure 14. Fastened reusable claw with cone pin

This conical pin is less ductile than the pin having four cantilever beams, but is not subject to disengage with rotation about its vertical axis, being symmetrical about that axis. Additional material was added to the tip of the cone to create a more substantial connection as shown in Figure 15.

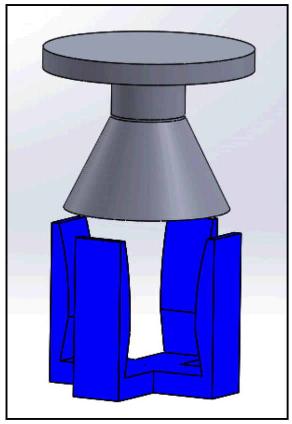

Figure 15. Reusable claw with modified pins

Pin modifications served to adequately fortify the junction without compromising excess ductility. This fastener also contains the potential to be tested for failure not only in tension, but also in compression, which is another area of interest for Sandia.

Puzzle Piece Fastener

The SolidWorks model of the puzzle piece fastener is shown in Figure 24 and Figure 25. The part to the right in Figure 24 will henceforth be referred to as Part 1, and the part to the left in Figure 24 will be called Part 2.

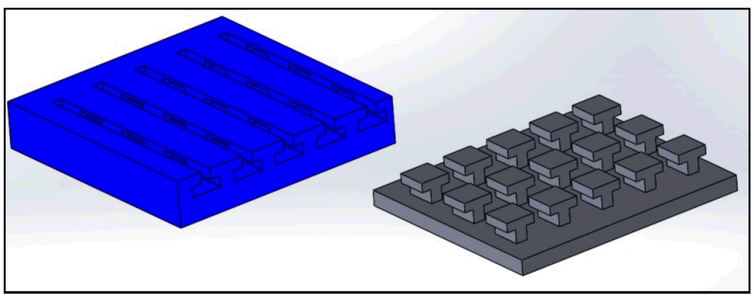

Figure 16. Disassembled puzzle piece fastener

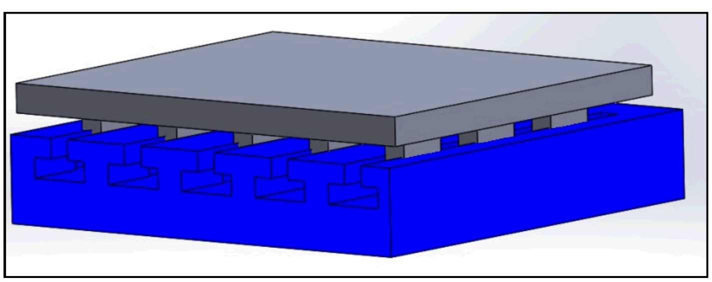

Figure 17. Assembled puzzle piece fastener

This fastener functions by taking Part 1 and sliding it into the corresponding slots in Part 2. Once the two pieces are attached as in Figure 25, the user would then pull upward on Part 1 to lock it in grooves present in the slots to lock the parts together.

Locking Shaft Fastener

The locking shaft fastener attaches two rods together, end to end. Figures 18 and 19 show the two parts of the fastener. This fastener functions by taking Part 1 in Figure 18 and sliding it into Part 2 in Figure 19.

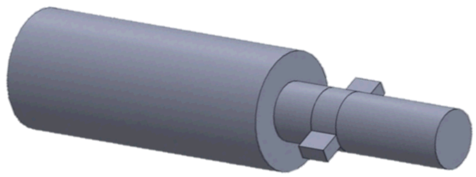

Figure 18. Locking shaft fastener part 1

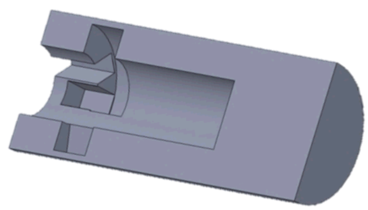

Figure 19. Section view of locking shaft fastener part 2

Propagating Claw Fastener

Figure 20 shows the propagating claw fastener, designed by analogy with the caps of a dry-erase marker.

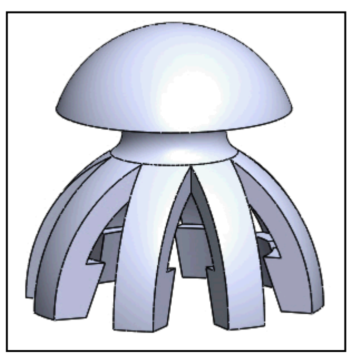

Figure 20. SolidWorks model of propagating claw fastener

The design can be divided at its neck into a pin on top and clasps below. The clasps form a claw which receives the pin by flexing outwards as a force is applied, deflecting enough to allow the pin through. Once the pin has entered, the claw returns to its undeflected position and, with the extruded lip on each clasp acting as an abutment surface, prevents the pin from retracting. Figure 21 shows the fastener in use, with the clasps encapsulating the pin.

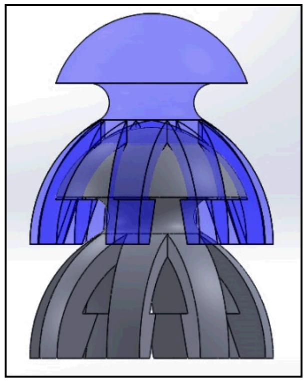

Figure 21. Attached propagating claw fastener

Reusable Clip Fastener

In a bike helmet, the clip can potentially unfasten if it receives a force from the side. For this design, the housing for the clip was made so the clip cannot be removed unless there is an active attempt to unfasten it with a tool. Figure 22 shows a SolidWorks model of the housing (left) and the clip (right).

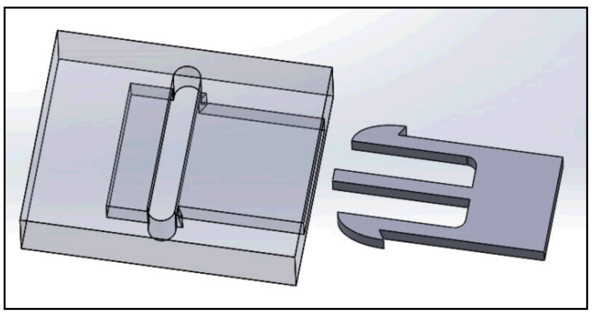

Figure 22. SolidWorks model of the reusable clip fastener

The top and bottom members of the clip deflect towards the center member when the clip is inserted into the housing. The width of the cavity within the housing expands near the center of the housing; once the clip reaches the expansion, the deflected members snap back to their original position to fasten the clip. Figure 23 shows the clip in the fastened position.

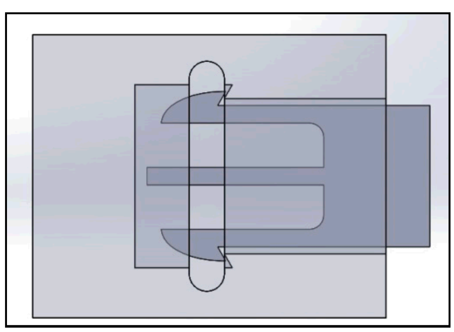

Figure 23. Fastened model of the reusable clip fastener

The slot in the housing allows for a tool to unfasten the clip by deflecting the top and bottom members towards the center. After the members are deflected, the tool can slide the clip out of the fastener.

Prototypes

To test functionality all nine fastener designs were prototyped, see Figure 24, in nylon 12 on the SLS machine at UT-Austin [4].

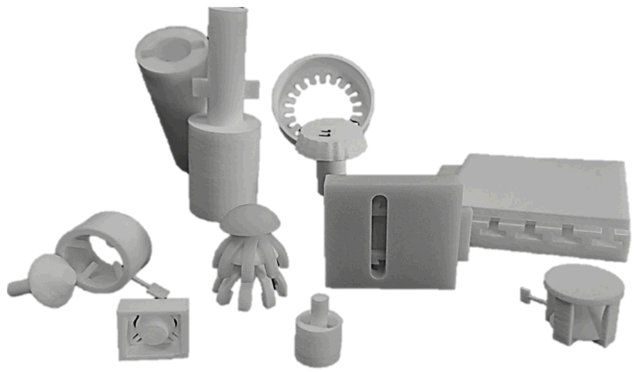

Figure 24. Prototypes of fastener concepts

Upon receipt of the prototypes, fit tests were conducted to determine if the designs fastened as expected. Out of the nine fastener designs, six fastened as expected and three did not fasten. Two of the three designs which failed the fit test used flexible members as their fastening mechanisms and would have benefitted from iterative prototyping. The permanent pin and cap design did not fasten because the cantilever beams around the cap were more brittle than expected; the beams snapped off before the pin was fastened. Similarly, flexibility issues caused failure in the guided icosafoil prototype. The locking shafts fastener failed the fit testing due to tolerance issues. The remaining designs were functional; however, certain drawbacks were realized during the fit tests. The reusable pin and cap allowed for excessive shifting of the pin within the cap. The permanent quatrefoil appeared to be fairly weak and was unable to remain fastened against even small forces.

Design Selection and Modification

In order to down select to the final designs, the functionality and testability of each design were considered. First, the permanent pin and cap, the guided icosafoil, and the locking shafts were eliminated due to their lack of functionality. Next, the permanent quatrefoil and the reusable claw were eliminated due to their relatively low strengths. Then, the puzzle piece fastener was eliminated due to testability; a large amount of material would be needed to attach sections for the tensile testing clamps. Finally, the reusable pin and cap, the reusable clip, and the propagating claw were chosen for more testing.

After design selection, design modifications were made to the chosen fasteners to accommodate tensile testing. Tapered extrusions were added on each end of the fastener to fit into the tensile testing machine. Stress analyses were conducted in SolidWorks to ensure the sections did not add stress concentrators to the design. The results of the tensile extrusion simulations are presented in Figures 25-27 below.

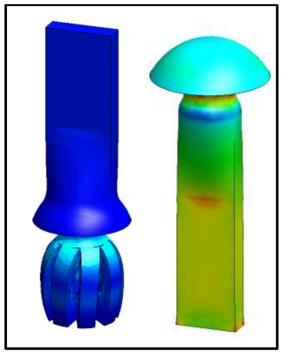

Figure 25. Stress analysis of design modification of the propagating claw fastener

As expected, the largest stress concentrations shown in Figure 25 are in the 'neck' of the design. The results of the simulations also indicated stress concentrators at a joint between two extrusions of equal cross section on the propagating claw fastener. These were experimentally determined to be software artifacts stemming from the extrusion process rather than realistic indicators of existing stress concentrators.

Figure 26. Stress analysis of design modification of the pin and cap fastener

The results in Figure 26 showed that the reusable pin and cap would fail at the abutment surfaces and not at the additional extrusions as desired.

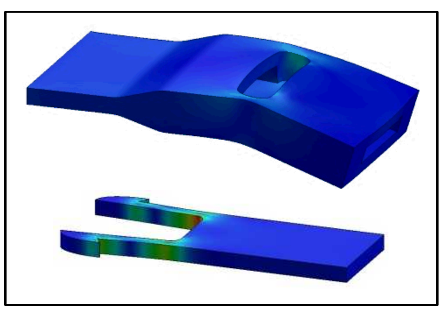

Figure 27. Stress analysis of design modification of the clip fastener

Simulations presented in Figure 27 also demonstrated that the reusable clip would function as expected. Bending occurs in the clip housing simulation as a result of fixing one end of the clip while applying a force to the other, which is the required method for finite element tensile simulations in SolidWorks. Bending in this case is caused by the design's asymmetry due to its window.

Experiments

The build-to-build variation testing was separated into two categories: location-to-location and day-to-day. For location variation, each fastener was built in nine locations on the build platform. For day variation, the location variation test was built three times. A tensile bar was placed in each group of fasteners for comparing the strength of the fastener with the strength of the AM material. The build layout for the variation testing is shown below in Figure 28.

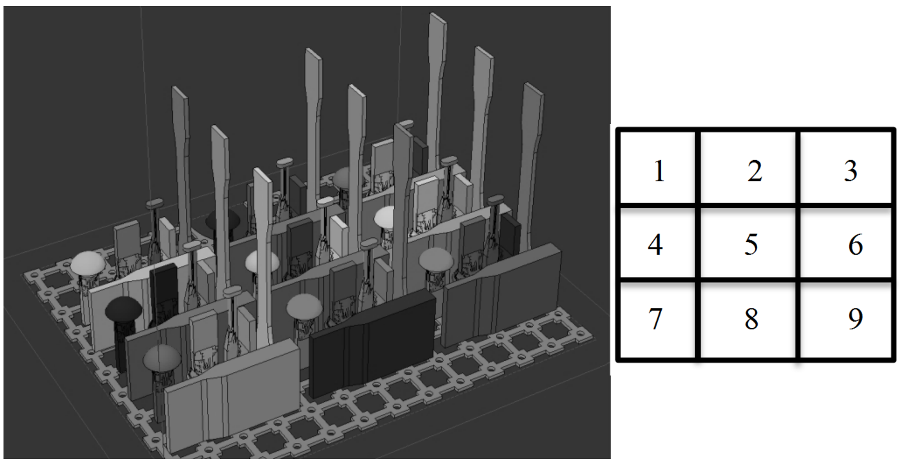

Figure 28. Build layout and numbering for variability testing

A SLS machine at Stratasys Direct Manufacturing using glass-filled nylon 12 was used for the variation testing [5]. A single machine was used for all three builds to eliminate a variable from the variation testing. Between the first and second build, the SLS machine underwent maintenance due to a failed build.

Results

Tensile tests were completed on the tensile bars and the fasteners from the first build; the results are shown below in Figure 29. Since the fasteners have varying cross-sectional areas, maximum load was used as the output metric for comparable results. The results for the propagating claw were not included because one of the legs fractured before the test was conducted.

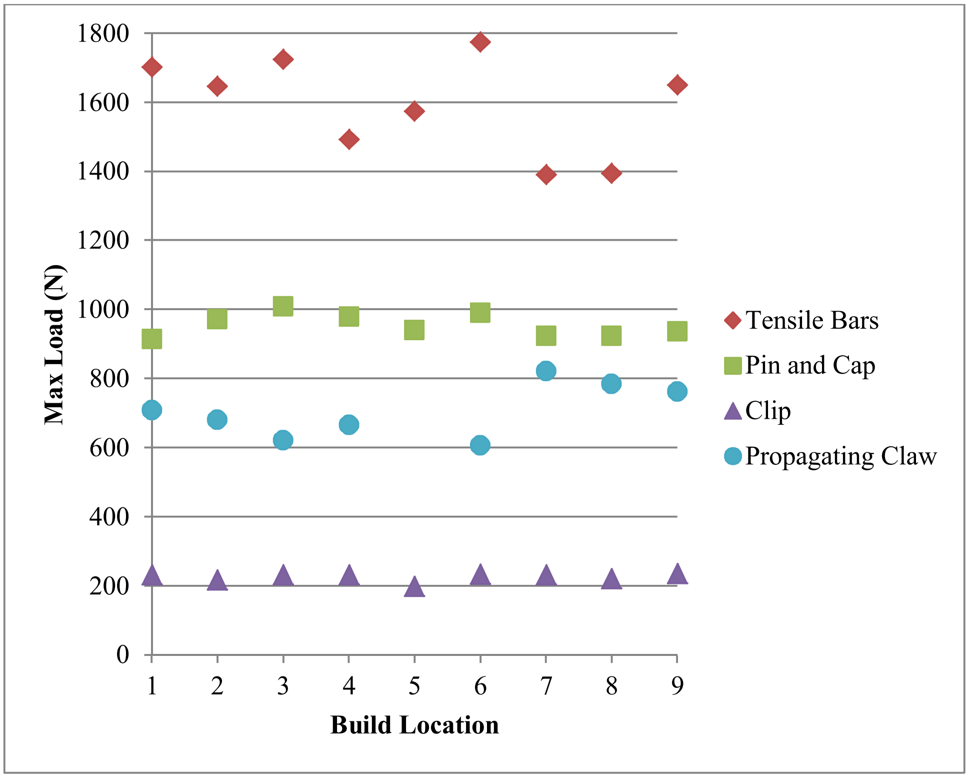

Figure 29. Tensile test results from the first build

The reusable pin and cap design exhibited the closest maximum loads in comparison to the tensile bars with the reusable clip being the furthest from them. The reusable clip failed at lower loads, in part, due to having the smallest abutment area. All of the specimens presented variation in maximum load dependent on the location. With this number of samples, a clear trend in the variation cannot be determined.

Once all three builds were tested, the maximum load data for each design was graphed to compare location data and day data. These graphs are presented in figures 30-32. After the maintenance between the first two builds, the propagating claw experienced tolerance issues that prohibited it from fastening; therefore, maximum load data for the propagating claw fastener was not collected for the final two builds.

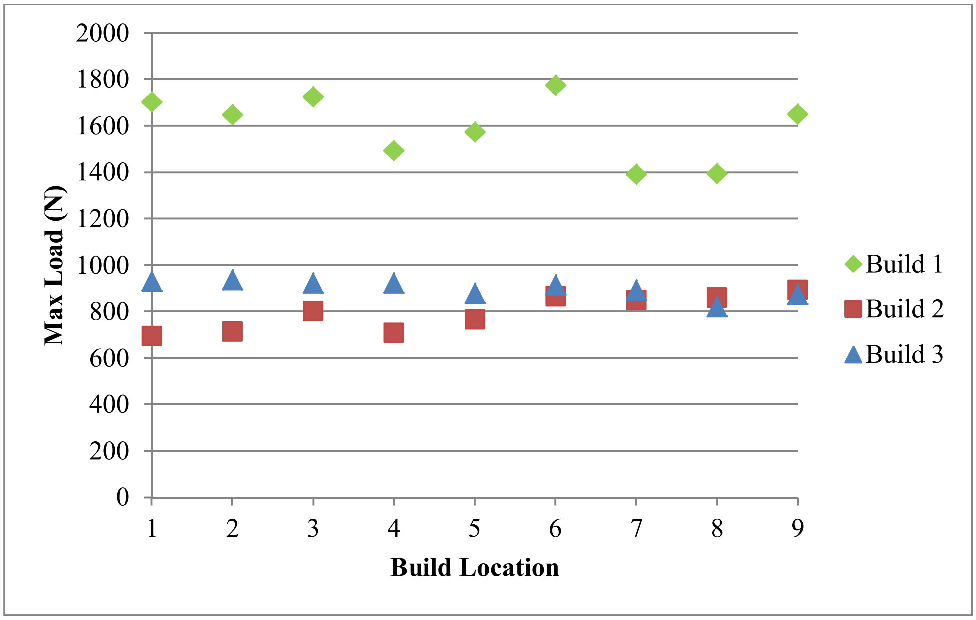

Figure 30. Max load of each tensile bar from the variation testing

In builds 1-3, the average maximum loads withstood by the tensile bars were 1595 N, 795 N, and 900 N, respectively. Figure 30 shows that there is a significant difference between the results of builds 1 and 2 while builds 2 and 3 are more similar. The only difference in builds was the maintenance conducted between builds 1 and 2.

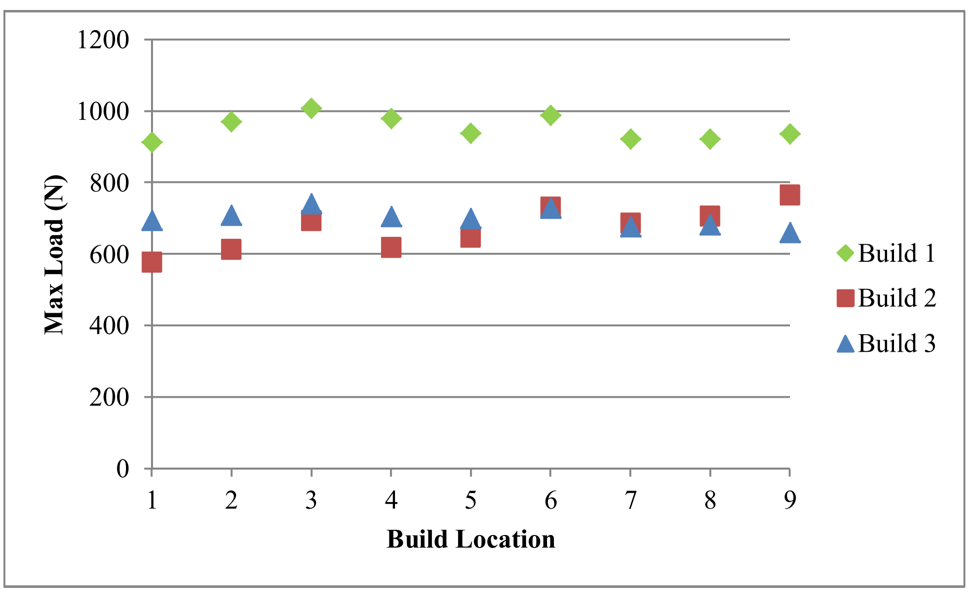

Figure 31. Max load of the reusable pin and cap design from the variation testing

In builds 1-3, the average maximum loads withstood by the reusable pin and cap were 954 N, 671 N, and 701 N, respectively. Figure 31 shows the similar variation between pre-maintenance and post-maintenance builds.

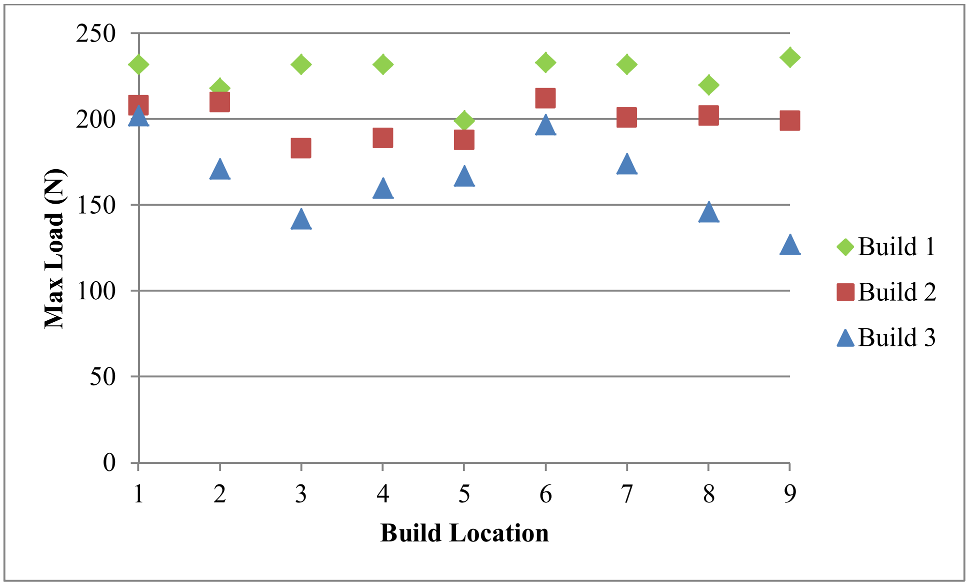

Figure 32. Max load of the reusable clip design from the variation testing

In builds 1-3, the average maximum loads withstood by the reusable clip were 226 N, 199 N, and 165 N, respectively. The reusable clip did not experience the same trends in variation between pre-maintenance and post-maintenance builds.

While variation was present between all locations and days, the machine maintenance seems to have had an impact on the maximum load reached during the tensile tests. At this point, more samples are needed to have a better understanding of variation in SLS part properties.

Future Work

Iterative design studies of each of the fastener concepts would greatly enhance their functionality and strength. Information on how the fasteners perform at a range of different sizes would provide beneficial information for their integration into AM parts. Studies in additional materials are necessary to increase the impact of these fasteners on AM design. An increased sample size will provide a better representation of variation across the build plate. With more samples, a property map of the build plate would be beneficial to AM part production.

Conclusions

This paper describes nine fastener concepts that can be integrated into additively manufactured parts to reduce the need of traditional fasteners. Out of the fasteners tested, the reusable pin and cap withstood the highest maximum load. The strength of the reusable clip could be improved with a redesign to have larger contact area between its abutment surfaces. Adjusting the tolerance in the propagating claw fastener is necessary to account for dimensional variation between builds. For the remaining six designs, iterative design would greatly improve their functionality and feasibility as AM fasteners.

In addition to testing functionality, replicating the fasteners showed that there is variation in part strength from location-to-location and day-to-day. A potential cause of the large difference between the first build and the remaining builds was that the SLS machine underwent maintenance due to a failed build between builds 1 and 2. More samples are needed to increase the understanding of build-to-build variability in selective laser sintering.

Acknowledgements

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