ME 450
Fall 2015 Semester
Final Report

Team 17
Metal Forming Force Measurement

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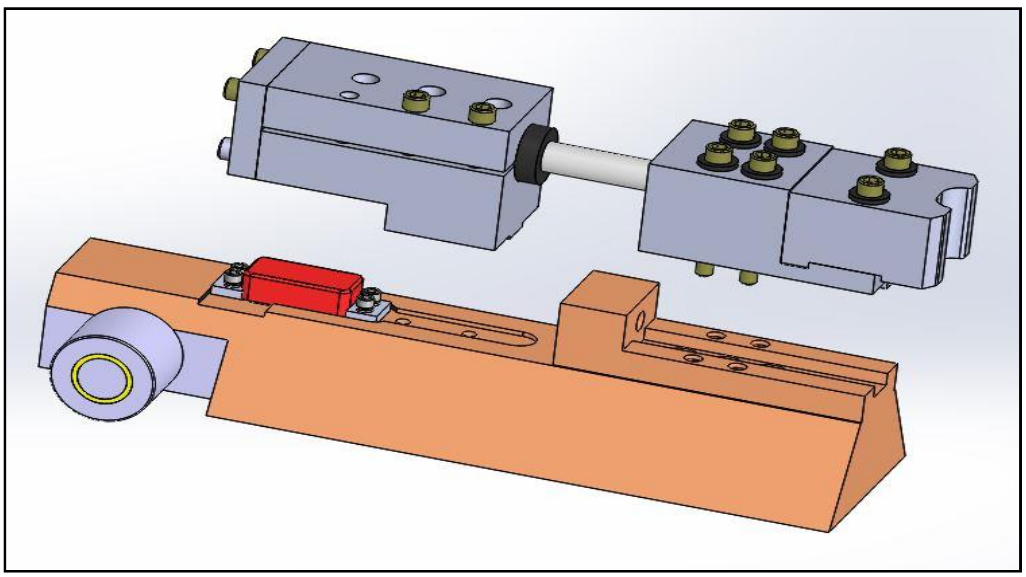

Executive Summary

Clips and Clamps Industries (CCI) produces small metal parts, many of which are formed using metal forming fourslide machines. CCI's fourslide machines have been experiencing failures and increased maintenance due to the usage of high-strength steels that require more force to form. The operators are not provided with information about the state of the machine during operation and thus do not know if they are exceeding the forming section's force limit. In order to minimize damage and maintenance, CCI has asked us to implement a sensor that detects the forces on the slide while the machine is in operation, to incorporate a safety control to automatically shut off the machine when a programmed force is exceeded, and to calculate the maximum tonnage rating on the forming section—specifically the front slide as this is the area prone to failure. This design must also be scalable so that it may be implemented on both the smaller, S3F and larger, S4F machines.

After initial research and defining the project scope, the next steps were identifying key design drivers, generating design concepts, and analyzing and evaluating those design concepts to fulfill the requirements entailed in the project scope. To begin concept generation, the problem was divided into subcategories and then concept ideas were created for the major categories. The major categories included type of force transducers, placement of force transducer, wire configuration, and safety features. 38 unique concepts were generated. From these concepts, three designs emerged using various design strategies such as researching existing solutions and technologies, speaking with CCI employees, and creating Pugh charts to prioritize all concepts. The top three designs were analyzed more fully leading to the selection of the final design.

After running FEAs on the slide and gathering feedback from sponsors at CCI and professors at the University of Michigan, the final design has been solidified as a Wintriss strain link sensor bolted to the top of the slide. Through a mockup made of foam, a model in CAD, and Solidworks FEAs of a static slide, data was gathered regarding strains on the slide to justify the location of the sensor while assuring that the design would not hinder the fourslide machine operation or compromise safety. The risk associated with the design has been assessed in both a risk analysis and FMEA, raising concerns with safety and potential failures.

The final design has been manufactured and is installed in a fourslide machine at CCI. To validate whether the design meets the project requirements, the strain link was calibrated with a load cell to ensure accuracy as well as tested to ensure functionality of auto-shutoff capability. Additionally, through theoretical modeling including finite element and fatigue analysis, the maximum tonnage rating was determined to be 4.5 tons. This maximum tonnage rating will be validated and further refined through empirical testing over time carried out by CCI.

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Section 1: Problem Description

Clips and Clamps Industries (CCI) mass produces a variety of small, metal parts, many of which are formed using fourslide machines. CCI's fourslide machines have recently been experiencing failures and increased maintenance due to the usage of high-strength steels that require more force to form. The operators are not provided with information about the state of the machine during operation and thus do not know if they are exceeding the forming section's force limit. As a result, the most recent breakdown of a fourslide resulted in over fifty-thousand dollars in maintenance and restoration costs for CCI. The restoration was particularly expensive due to the fourslide manufacturers no longer being in business therefore the restoration was outsourced.

In order to avoid another major breakdown as well as minimize damage and excessive maintenance, CCI has asked us to implement a sensor that detects the forces on the slide while the machine is in operation, to incorporate a safety control to automatically shut off the machine when a programmed force is exceeded, and to calculate the maximum tonnage rating on the forming section—specifically on the front slide as this is the area prone to failure. This design must also be scalable so that it may be implemented on both the smaller, S3F and larger, S4F machines.

Section 2: Background

To begin, fourslide machines are old technology, originally designed by Eli J. Manville in 1855 [1] for the mass production of safety pins. Though an old design, a fourslide machine is very complex as it is almost a purely mechanically driven system. A fourslide machine utilizes several helical gears and cams to synchronize the motion of a feeder to pull material through, a press to puncture holes in the material, and multiple slides that form the material around a center post [2]. The forming section is made up of four slides perpendicular to one other. On each of these slides is a tool used to form the material. Each part will have its own specific set of tools necessary to form that particular part. As seen in Figure 1, the coiled material is first fed through a straightener and pulled through using the feeder. Afterwards, the straightened material goes through the press section where one or multiple holes may be punched depending on the part. Then the material is fed further past the center post where the slides sequentially form the material around the center post. [3].

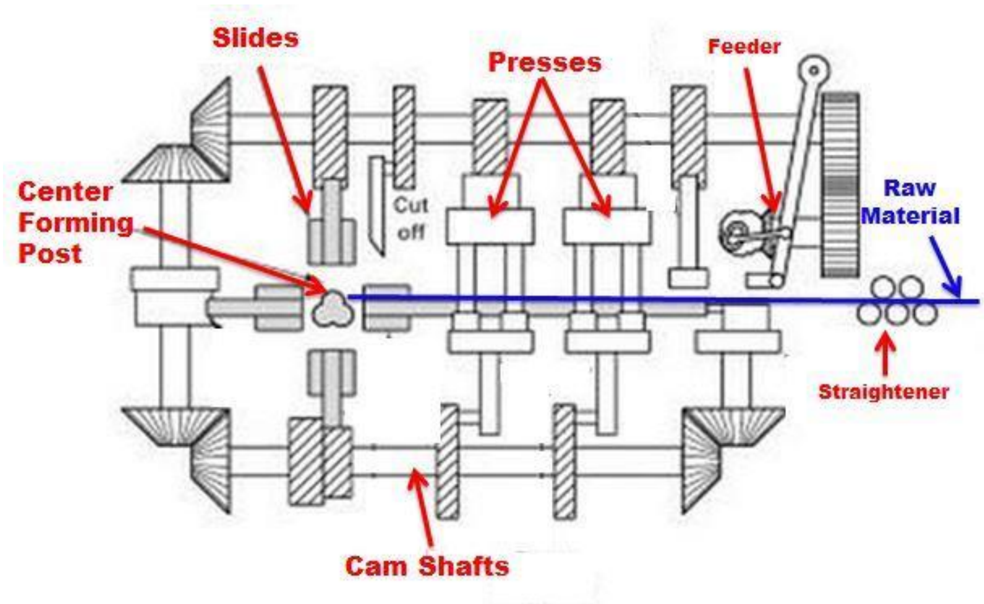


Figure 1: Fourslide Machine Schematic [4]

As specified by the manufacturer, the press section of an S4F model fourslide machine has a maximum tonnage rating of 30 tons [5]; however, the fourslide section has no such rating.

Research into force measurement in slide forming machines showed that force measurement on the slide of these machines does exist. As it turns out force monitoring technology in manufacturing has grown and evolved a lot over the years. While it originally was used to prevent overload in metal stamping presses, it has grown into a means of also protecting tools, improving part quality, and vastly speeding up the setup process. The biggest benefits force monitoring on slide forming machines offer are improved process/part quality, reduced machine set-up time, improved production control, and to enable analysis of machine condition [6]. These benefits are achieved by applying peak and signature analysis to metal forming processes.

Signature analysis is a method of establishing a signature response for a manufacturing process when everything is running correctly and good parts are being produced [8]. The signature is very unique to the process and should be produced every time the process is run correctly. The signature response can be characterized in terms of many different parameters during the manufacturing process with the most common being force as a function of tool position or time [9]. Using data collected from the sensors, signature analysis systems record and store the signature response and can analyze future responses of runs against the signature using a microprocessor [10]. The quality of the part produced is dependent on the forces used to create it, and by monitoring the forces and making sure they are consistent you can improve the consistency and quality of the parts that are produced [6]. CCI requested a means of using force monitoring to prevent their machines from breaking down and having extreme machine maintenance and signature analysis accomplishes this as well. Deviations from the established signature can be used to indicate the machine isn't running properly which could be a result of a tool needing to be changed or the machine re-worked. When the response falls outside of a certain quality window, the signature analysis microprocessor will shut down the machine. At this point the force response curve can be compared with the signature response to see deviations and analyze what went wrong so that the tool can be replaced or the machine be re-worked accordingly [8]. CCI decided that signature analysis was beyond the scope of what they needed. However, this research still provided informative background information on how force readings can be used to improve the machining process and the same fundamentals can be applied when only outputting a max force reading during a stroke of the machine.

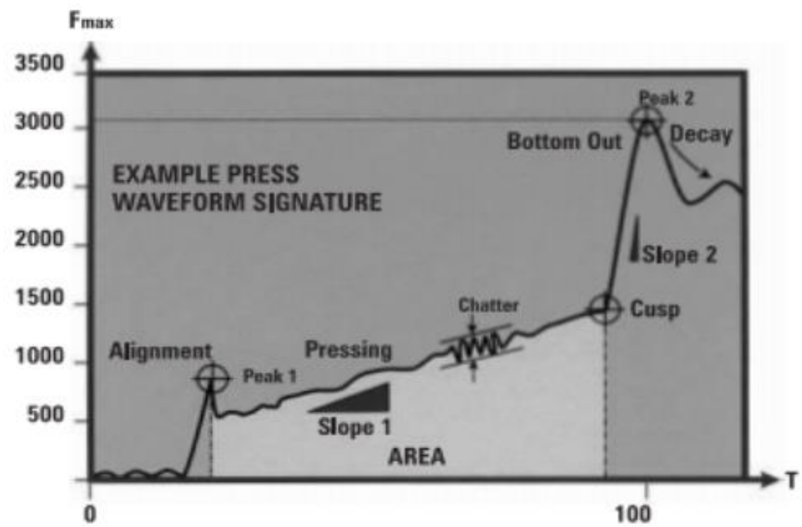


Figure 2: Job specific waveform signatures allow for more accurate process control [8]

In order for the signature analysis to be reliable it is necessary to make an accurate measure of the force within the slide. The process of choosing the ideal force measurement system is crucial to developing the most accurate and reliable means of measuring the force in the fourslides for CCI. The most important thing in making a valid force measurement is the placement of the sensor used to measure the forces. The sensor is most useful when placed in a location where the force measured is directly related to the force applied by the slide. In addition the sensor is most effective when oriented properly so that the applied force is placed upon the sensors principal axis [11]. The most commonly used sensor in force monitoring of slide machines are strain gauges [12]. Strain gauge force sensors consist of an elastic element, usually machine metal, and electrical resistance strain gauges that are bonded to the elastic element. The essential component in a strain gauge that allows for measurement is a Wheatstone bridge circuit. When a force is applied to this sensor, the elastic material deflects in either tension or compression. The strain gauges resistance is altered by the deflection that occurs and the force is measured by measuring the change in resistance [13]. The strain gauges perform best when connected in a Wheatstone bridge configuration to maximize the effectiveness of the load cell and to minimize environmental effects. The change in resistance in the strain gauges is measured by the output voltage of the bridge in response to an applied input voltage and can be calibrated to measure the force being applied [14, 15].

There are three commonly used configurations that are used to implement a strain gauge into the slide area to measure the force generated to form the parts. The first configuration consists of counter boring a pocket into the rear section of the slide and mounting a bolt on strain gauge to the slide. The gauge is placed along the longitudinal axis and in the smallest cross section possible to maximize the force output signals [16]. Because the gauge is located at the rear section of the slide, not of all the forming force is transferred through the gauge and field calibration is required. This configuration has the advantage of being universal to all parts being formed and tools used because the gauge is mounted onto the slide and not the tool holder.

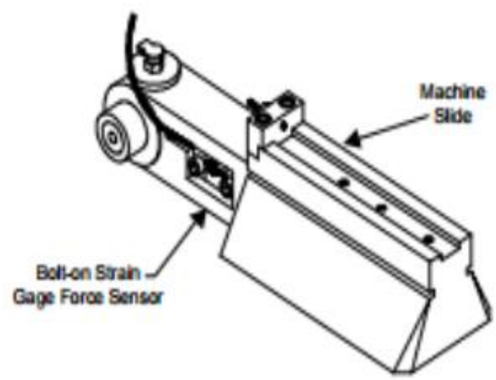


Figure 3: Bolt-on strain gage mounting in recessed machine slide for space savings [6]

The second configuration uses a cell housing and a loading pin to mount a load cell to the back of the tool holder that attaches the tool used to form the part to slide. Since the load cell is closer to the tool in this configuration and the forming force is transferred through the load cell, the resulting signal is more indicative of process forces acting on the tool itself. This configuration can be universal for several different tools as long as they utilize the same tool holder to be attached to the slide.

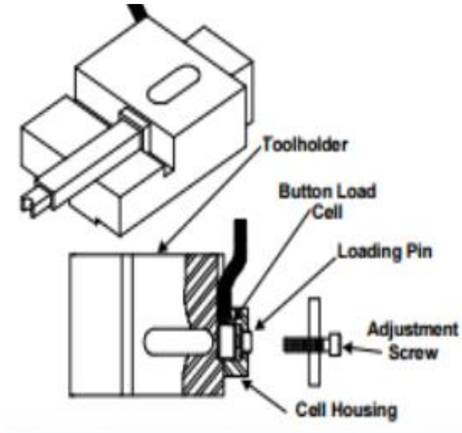


Figure 4: Strain gage or load cell mounting on rear of tool holder for increased accuracy [6]

Finally, the third configuration consists of mounting a cell housing that contains a load cell onto the front of the tool holder where the tool is mounted to the tool holder. This configuration has the advantage of transferring all of the forming force through the load cell leading to the strongest and clearest force output signals and eliminating the need for field calibration. However, this configuration is not universal and may not work for all tools, as they come in different shapes and sizes [6]. This research guided the development of the force measurement system for this project and ultimately the first configuration was chosen to allow for a universal configuration for all parts being formed.

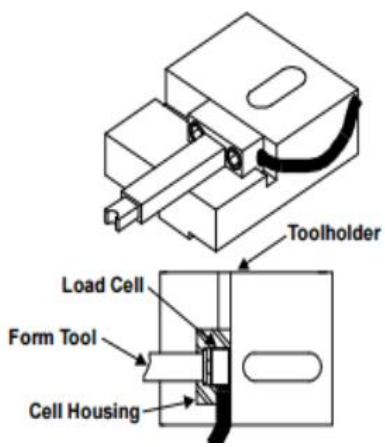


Figure 5: Load cell placement behind tool for optimal force measurement accuracy [6]

Section 3: User Requirements & Engineering Specifications

There are a variety of user requirements and constraints addressed in this project as shown in Table 1 below. Table 1consists of a prioritized list of these requirements, the engineering specifications that satisfy requirements, and the rationale behind the specifications.

Table 1: User requirements and engineering specifications that satisfy them.

User Requirements	Priority	Specification	Rationale
Sensor conveys forces on front slide	High	Accuracy of ±10%	SmartPAC resolution limitations
Compatibility with SmartPAC output monitor	High	Buy Wintriss Strain Link	Wintriss is the manufacturer of SmartPAC
Doesn't interfere with functionality of machine	High	Ability to run a whole day without affecting part quality	Examines functionality of sensor over extended period of time
Scalability for all fourslide machines	Moderate	Within 2.375 in x 4.875 in x 1 in	Dimensions of SF3 slide, hence scalable
Safety/Aesthetics	Low	Within 2.375 in x 4.875 in x 1 in, Bright Color	Easy for workers to view
Cost Effective	Low	<$500	Initial budget allocated

The primary and prioritized user requirement of the sensor on the fourslide is to be able to measure the forces present on the front slide while the machine is in operation. This is thoroughly important as the reason the fourslide machine is breaking down is due to excessive forces on the slide section of the machine and thus this sensor needs to be able to monitor the forces with precision. Therefore, the specification is that the sensor must be able to have an accuracy of ±10 % of the actual forces registered in tonnage. The reasoning behind this number is that the resolution of the SmartPAC is 0.1 tons and taking in to account that the average forces are around 3 tons, that 10% is a reasonable number taking into account accumulation of errors. This high level of accuracy is needed because if it is not that accurate the actual forces upon the machine could be greater than the tonnage rating, leading to machine failure and excessive repair costs. Nevertheless, it is difficult to implement a sensor in such a minimal amount of space and there is an ever present uncertainty attributed to all sensors, leading to an accuracy of ±10 % being ideal for this project.

Adding on, another prioritized user requirements is that the sensor needs to be compatible with the SmartPAC output monitor as per CCI's request. This requirement is easily satisfied by implementing the Wintriss strain link as our sensor because Wintriss is also the manufacturer of the SmartPAC with the same operating voltage being needed for both. Furthermore, a crucial requirement expressed by CCI is to make sure that the sensor doesn't interfere with the functionality of the machine. The engineering specification to aid this is by running a part for a whole day and viewing whether the part quality is affected by comparing a part in the beginning to a part in the end. This is done in order to examine the functionality of the sensor over an extended period of time and whether it causes a change in quality of the part as the number of cycles increase. Though difficult to quantify part quality, the two different parts generic specifications will be measured and compared as well as a qualitative physical assessment in order to assess the variability of the parts.

Adding on, a moderately high priority requirement placed by CCI that the sensor had scalability so that it could be implemented in every fourslide machine throughout the factory and used to monitor all the forces. Though a difficult problem to deal with, in order to comply with it the sensor will be created for the smallest front tool size constraints, 2.375 in x 4.875 in x 1 in [19], and then scale up appropriately whenever needed. By implementing this policy, the sensor would fit in any fourslide machine in the factory as it can be used in the smallest one.

Lastly, an extraneous requirement that is not crucial in this project is the safety and aesthetic features of the sensor. Though not a priority, it is satisfied by fitting the dimensions of the sensor to that of the slide constraints, 2.375 in x 4.875 in x 1 in [19], as not to interfere with everyday workers' functions as well as trying to make it a bright color so that it is easily visible and hence not damaged as much. Also, another extraneous requirement that is not crucial yet still important in the design of the sensor is the budget. It has been agreed upon with CCI that it should be within the budget of $500 yet if there is a crucial need for a component that will better the sensor as a whole it will be discussed with the managers and additional funding will be granted as seen fit.

Section 4: Concept Generation

The concept generation and concept selection process is cyclical. As such, this process was performed several times until a truly viable design was generated. The same general steps were followed for each cycle, however, the process discussed in this report details the first iteration of the cycle and the initial final concept discussed is not the design that was implemented as a prototype.

To generate initial concepts for the design, a variety factors were considered to solve the presented problems. The process began with analyzing the task at hand and creating a functional decomposition (Figure 6). This functional decomposition highlighted the features the design had to incorporate to be considered successful and outlined general steps to accomplish these features.

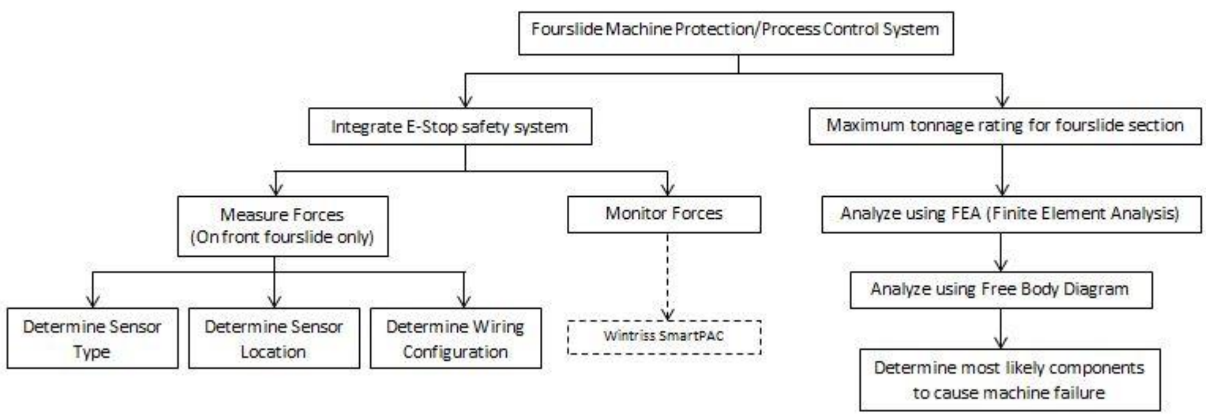


Figure 6: Functional decomposition flow chart showing the features of the design project.

As shown by the functional decomposition, there are several parts relevant to the problem. Firstly, a sensor must be integrated with the fourslide machine to measure the forces on the front slide. The sensor was evaluated based on the concept selections of type of sensor, location of the sensor, and the wiring configuration of the sensor wiring.

The second part of the problem was to determine the maximum tonnage rating on the fourslide section. In terms of concept selection, this was further broken down to include the method of analyzing the maximum tonnage rating and the type of software used to do the analysis.

To generate the concepts for the design, ideas were brainstormed for the major categories derived from the functional decomposition. The first major category was the different type of force transducers that would fulfill the function of measuring forces on the front slide. The next category considered was where the transducer should be located to measure the correct forces. Another category was how the wires should be configured to carry the transducers signal to the monitor, prevent safety hazards, and prevent fatigue in the wire. Furthermore, ideas were created for safety features for the transducer and the fourslide machine which can be implemented to each concept generated before. Finally, the last category was the different types of analysis that can be used to derive the maximum tonnage rating. The concepts brainstormed in these categories were then melded together, one from each category, to create completed designs.

In the first concept drawing (Appendix B.1), the type of force transducer implemented is a micro bolt-on strain gauge, to be placed on the side of the slide where it would be counter bored in a recess cavity with a protective covering. There would be threaded quick disconnect on the strain gauge for easy maintenance. Also, the wires would have a strain relief wire holder holding them in place to increase wire safety and to help bring the transducer signal back to the monitor.

The second design concept drawing (Appendix B.2) consists of an adhesive strain gauge to be used as the force transducer but it would be placed on the top of the tool holder with cell housing as that is the ideal way for maximum compression. There would be a milled slot throughout the slide in which the wire would be taped to as it keeps it secure and helps bring the transducers signal back to the monitor. Furthermore, for added safety there would be a plastic box around the strain gauge to minimize damage to it and increase the durability.

The third design concept drawing (Appendix B.3) consists of a micro bolt-on strain gauge and would be placed on the bottom of the slide where it would be counter bored in a recess cavity. There would be a milled slot through the bottom of the slide, which the wires would go through, and then a strain relief wire holder at the back of the slide where the milled slot ends and the wires would go through to bring the transducers signal to the monitor.

The final design concept drawing (Appendix B.5) consists of a wireless shear pin to be used as the force transducer. It would be placed within the pin slot in the slide and has wireless capabilities therefore no physical wires would need to be used.

Apart from the integrated designs, a major category for which concepts were generated was the type of analysis to derive a maximum tonnage rating. The most basic concept generated was to create a free body diagram and analyze all the forces that were present on the fourslide to get a basic understanding of how and where failure could occur on the components of the fourslide. A more complex concept generated was to use Finite Element Analysis using Hyperworks or Solidworks on all components that make up the slide and try to simulate the movement of the actual machine. A more unique idea was to contact companies who had listed tonnage ratings for forming machines and enquire about their methods, and then follow the same steps.

Section 5: Concept Selection

After completing the concept generation stage with four complete concepts, the options needed to be narrowed down and a final complete concept selected. The four major concepts generated were broken down into their sub-concepts. All of these sub-concepts were categorized into one of four sub-functions: force measurement, force measurement placement, safety shut-off, and wire configuration. The sub-concepts were graded separately from the complete concept to which they originally belonged, allowing all combinations of sub-concepts to be considered. The sub-concepts from each of the four categories that were graded the highest were then combined to form a complete final concept that met the user requirements.

To implement an unbiased method of choosing a final concept, a series of Pugh charts were utilized (Appendix C), one for each sub-function category. The criterion set, against which to evaluate the concepts, varied for each sub-function (Table 2). The selection criterions were rated from one to three to weight the relative importance of each criterion. Each sub-concept received a score in the selection category from zero to six, the higher numbers being more effective. The criterion's score was multiplied with the sub-concept's respective score in that particular criterion and then added up with the rest of the scores for that sub-concept. This left a total score for all the different sub-concepts; the highest number conveyed the best overall sub-concept for that category.

Table 2:Criterion against which each sub-function was evaluated.

Force Measurement	**Mounting Design**	**Safety Shut-Off**	**Wire Configuration**
Feasibility	Ease of Maintenance	Manufacturability	Manufacturability
Scalability	Scalability	Feasibility	Durability
Cost Effectiveness	Cost Effectiveness		Feasibility
Provides Part Quality Control	Provides Part Quality Control		
	No Hindrance to Operation		
	Feasibility		
	Manufacturability		

Providing part quality, feasibility, not hindering the slide machine, and scalability were all weighted to three as these were all user requirements and essential to a successful product. Ease of maintenance, ease of manufacturability, and durability were ranked with a two because these were desired properties that would detract functionality from the design if they were lacking, but that ultimately could have been worked around if needed. The cost effectiveness was ranked at a one because, while important, CCI preferred a solid design even if it were expensive.

Based on this Pugh chart analysis, the highest ranked sub-concepts were compiled into one initial final concept (Figure 7). The final concept chosen from the initial round of the design cycle comprised of a bolted on strain gauge placed on the bottom of the slide in a recessed cavity. The strain gauge was covered by a plate that would be set flush with the bottom of the slide; this would be done by counter boring around the cavity. The wiring connecting the bolted strain gauge to the monitor would be run through and glued into a slot milled in the base of the slide and then fed through a hole drilled in the safety pipe that runs around the parameter of the fourslide machine. As the wire leaves the slide, there would be a strain relief holder. In this initial final design, the automatic safety shut-off was selected as the safety shut-off mechanism; however, many of the safety shut-off designs discussed were viable.

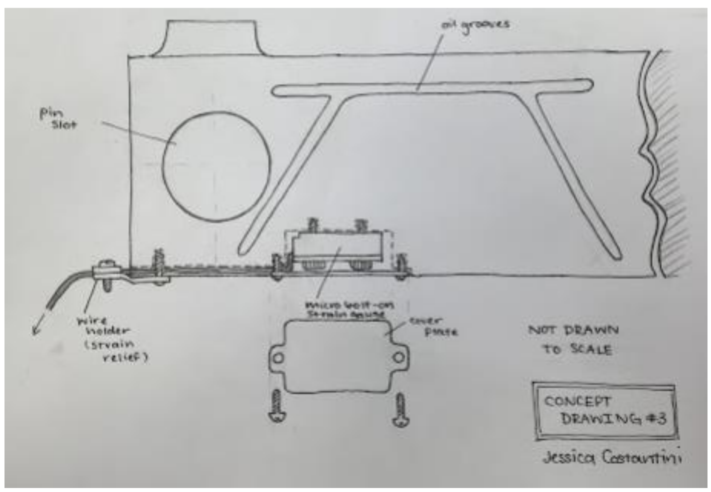


Figure 7: A sketch of the chosen design through Pugh chart analysis. This design was not the prototype actually implemented on the fourslide machines, but rather the first iteration of a final design concept that changed with further analysis.

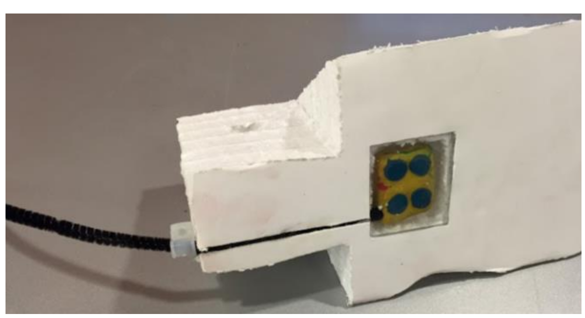


Figure 8: A mockup of the chosen concept. The strain gauge is the yellow and blue rectangle, the black pipe cleaner is meant to be the wire, and there is a cover plate over the strain gauge, protecting it.

The Pugh charts were used as an initial comparison between concepts, however, the sub-functions are related to each other in various ways that the Pugh charts did not consider. For example, a wireless wire configuration was not viable without the wireless shear pin sub-concept chosen as the force measurement. Because of this, the advantages and disadvantages of each design as well as the relation between sub-concepts had to be taken into account. The Pugh chart recommended that the force measurement mount be located beneath the slide. Because of this, durability of the force measurement device became more important and size less so, leading to the decision of the bolted on strain gauge. To conserve space beneath the slide, to not interfere with the fourslide machine motion, and to improve durability, a plastic wire guide was no longer considered and ultimately a milled slot was chosen to feed the wire through. The safety shut-off was not as dependent on the other sub-functions, and it was cost effective to use the automatic shut-off that will be programmed into the machine SmartPAC interface. These decisions will be discussed more in depth in the following paragraphs.

The initial final design had both advantages and disadvantages. It would be scalable to the other fourslide machines because the strain gauge placement on the bottom of the slide would have less interference from other parts of the fourslide machine than the top of the slide. Also, the bottom of the slide flairs out, giving a wider place with which to work. However, placing the strain gauge on the bottom of the slide would make it more difficult to perform maintenance on the strain gauge. The operators would have to stop the fourslide machine and take it apart to access the strain gauge. The slide is also lubricated with oil and has oil grooves running across the surface below the fourslide main table. This may cause a problem with the strain gauge being placed on the bottom or side versus the top of the slide, as the cavity may become filled with oil. Extra emphasis would have to be placed on tight tolerances when machining the strain gauge recess and further research would have to be done to find ways to prevent the oil from gathering in the milled slot.

The milled slot chosen using the Pugh charts would have been a good option because it would be easier to manufacture than drilling a hole all the way through the slide, which is made of hardened steel. The milled slot would also not be protruding from the bottom of the slide as a plastic runner for the wire, another possible design, would have been. The milled slot, however, would have been more difficult to keep free from oil, which may have caused oil to flow into the strain gauge cavity. Although going wireless for wire configuration would have been the best option, it was not an option while using the strain gauge as force measurement; it was not a feasible concept.

The bolted on strain gauge was chosen initially because it balanced price with frequency of response. Because the strain gauge would have been mounted underneath the slide, where maintenance is more difficult, a more durable strain gauge would have been needed versus an adhesive strain gauge that, while inexpensive, is not particularly durable. The adhesive strain gauge would have been a good choice in sub-function if not mounting the sensor on the top of the slide, as this would have allowed ease of maintenance for replacing the device. Introducing a force transducer shear pin to the fourslide machine was another popular concept, however it had very high prices which would have been difficult to implement in different machines at CCI.

The automatic safety shut-off was chosen from the safety shut-off sub-concepts because it was free, it came with the software package that CCI will use, it was effective, and it avoided over-designing. Also, a few of the concepts generated were not within the range of control to implement. For example, the break-away tooling was a feasible idea, but CCI changes out the fourslide tooling every time a new part starts to be produced. They also design their own tooling and, therefore, would have to design around this concept of break-away tooling. A variety of concepts scored close to each other in the Pugh chart for safety shut-off concepts, specifically the break-away bushing, shear pin in the cam shaft, and this automatic shut-off all scored in the thirties, therefore, implementing more than one safety shut-off was considered.

The process explained in the concept generation and concept selection sections details the first iteration of the concept generation and selection cycle. After additional consideration, another critical user requirement of SmartPAC compatibility of the sensor was discovered. This prompted another iteration of the concept generation and selection cycle that led to the true final design. The same general methods as detailed in the concept generation and concept selection sections of this report were utilized. The alternative concepts from this iteration of the design cycle are located in Appendix D. The true final concept design is discussed in its entirety in the final design concept section.

Section 6: Key Design Drivers and Challenges

The goals for this project included preventing future damage to the SF4 fourslide machine by determining a maximum tonnage rating for slide forming process and implementing a force measurement system to ensure the machine operates below this rating and within process control limits. Fourslide machines are very old and are no longer manufactured, so few references are available to help determine the limitations of fourslide forming sections. Additionally, the manufacturer did not set a maximum tonnage rating for the slides. As a result, various in-depth analyses on the forces acting within the machine needed to be performed—specifically on the components that were most likely to fail and that limited the capability of the machine. To ensure the machine did not exceed the tonnage rating, a force measurement system was implemented on the front slide of the machine. The key design drivers of the force measurement system were identified as: measurement of the appropriate force, scalability, location of the sensor, safety of the machine, operator, and sensor, and compatibility with the SmartPAC interface. This had to be accomplished without hindering the performance of the machine. Additionally, for the force measurement system to be effective, the maximum tonnage rating had to be reliable.

Measurement of the appropriate force was an important design driver. The force measured was compared to the maximum tonnage rating to automatically shut-off the fourslide machine and facilitate machine safety. This measured force would also be used to inspect part quality during the forming process, a user specification. As a result, determining the correct location and orientation of the sensor that captured this force was important as well. The location of the sensor was driven in turn by the design driver of scalability; whatever location chosen for the sensor on the larger S4F slide had to be repeatable for the smaller S3F slide. It was challenging to find a spot that allowed measurement of the correct forces while allowing for scalability across the types of fourslide machines and that did not interfere with normal machine operation.

The force measurement system also had to be designed so that it did not impact the performance of the fourslide machine. The wiring and sensor placement had to be placed so that when the fourslide machine cycled, nothing impeded operation. In addition, the wiring and sensor placement had to be optimized for operator safety. This was of special import as no operators should have been getting injured due to this design.

In order for the force measurement system to be effective, a reliable max tonnage rating had to be determined. If it were not reliable and a valid representation of what the slide forming process was capable of sustaining, it would not be of use with the force measurement system and would not have been used to prevent machine failures. It was challenging to determine a reliable tonnage rating.

Section 7: Concept Description

The final design of the S4F slide as shown below in Figure 9 includes a Wintriss Strain Link mounted on the slide below the modified gas pack tooling. The Wintriss strain link was chosen due to its compatibility and ease of integration with the SmartPAC controller. In fact, Wintriss is the manufacturer of both the strain link and the SmartPAC; thus, the sensor is specifically equipped for the $5V_{DC}$ excitation voltage of the SmartPAC controller. Additionally, the strain link has a built-in amplifier. This immediate amplification on the strain link significantly reduces the chance of ambient electronic noise affecting the strain link signal to the SmartPAC controller.

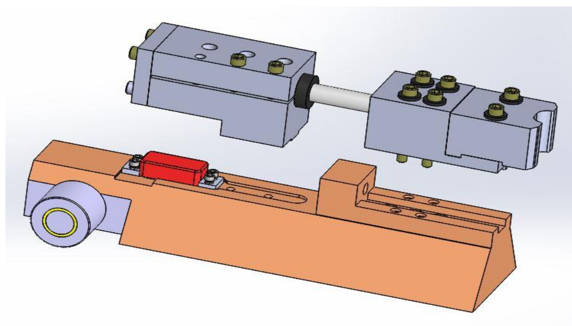
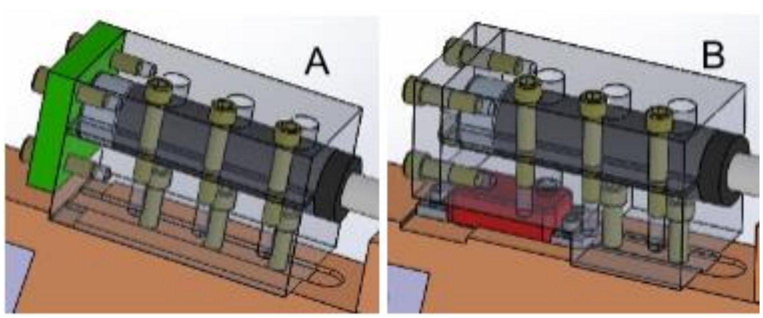


Figure 9: The Wintriss Strain Link is mounted on the top of the slide underneath the modified gas pack tooling in a location that has sufficient strain to allow tonnage monitoring.

Thought the Wintriss strain link is larger in size than other considered sensors, it still fit within the size constraints to meet the scalability requirements. In order to accommodate for some machines with additional gas pack tooling, modifications were necessary. A milled slot with three bolt holes was originally used to mount the gas pack tooling and secure it in place. To house the strain link, the milled slot was widened from ⅞ Inch to 1¼ Inches and the length of the milled slot was lengthened by 1 inch. This allowed the gas pack tooling to be mounted on the front two bolt holes while the strain link was mounted over the third hole (Figures 10A & 10B). The wiring exits the side of the strain link and is run through an opening to the side of the slide.



Figures 10A & 10B: The original and redesigned gas pack tooling, respectively. The new design removes material from underneath the gas pack and reduces the number of bolts securing it to the slide from three to two.

The placement of the sensor behind where the gas pack tooling acts on the slide ensures that the measured forces are more accurate. The strain link is then able to effectively measure both the force acting through the gas pack tooling as well as the front tooling. Moreover, mounting the strain link on top of the slide requires minimal machining and allows for fast and easy maintenance whereas recessing a cavity on the bottom or side of the slide is far more cumbersome. In addition to ease installation and maintenance, top mounting also does not introduce large stress concentrations in the slide unlike recessing a cavity. Since less strain will be induced, there is a smaller chance of failure and fatigue to the sensor and to the slide.

Though the Wintriss strain link is large and cumbersome and requires modification to the gas pack tooling, this concept is the best compromise of all of the design concepts. The Wintriss strain link offers a versatile design that is durable, yields low noise, and is compatible with the SmartPAC controller. It has been determined that this is the best design; however, two other alternative designs were investigated and are described in further detail in Appendix D.

Section 8: Engineering Analysis

Finite Element Analysis

A simplified force body diagram of the slide (Figure 11) was drawn to gain a better understanding of the stresses and strains developed within the slide during forming. A distributed load was applied at the top of the slide, which is the tool pushing back on the slide. The cross section where we are going to mount the sensor was analyzed to view the effects of the distributed load. A bending moment around the z axis occurs to balance the distributed load. As a result, there is a tensile bending stress at the bottom of the slide and a compressive stress at the top face of the slide both at a distance y from the axis of symmetry of the cross section. Thus, the stress caused by the compressive stresses on the top of the slide will cause strains in the x direction which is what the strain link will measure. The diagram was simplified by ignoring the friction forces acting on the sides and bottom of the slide as they will be negligible compared to the forming forces exerted by the tooling and pin.

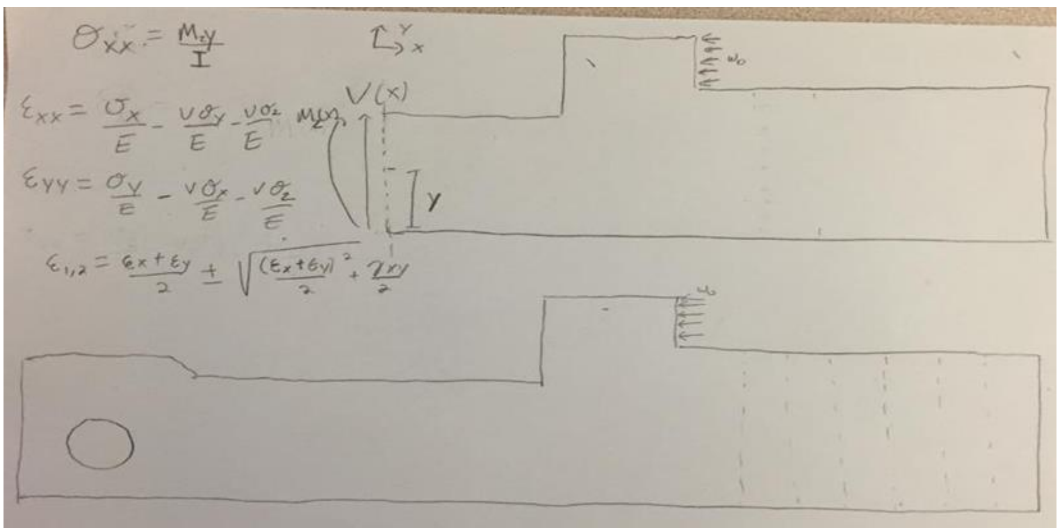
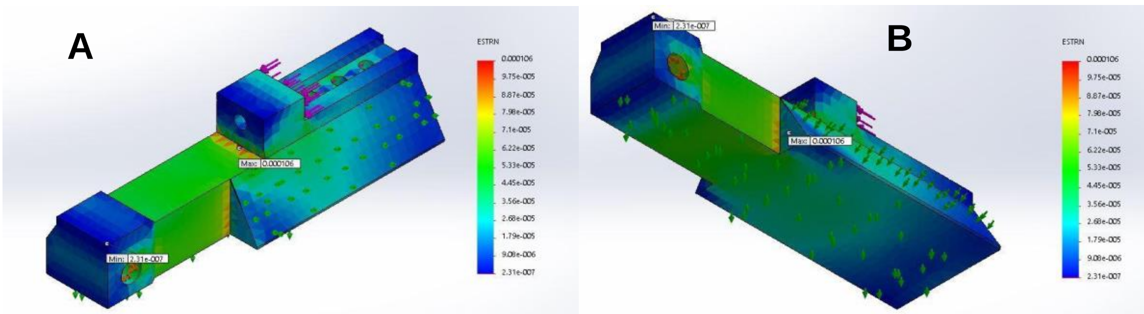


Figure 11: Simplified free body diagram of the slide during forming with relevant equations. Friction force along the sides and bottom of the tooling was neglected.

After completing a cursory free body diagram of the slide, a more sophisticated method of determining the strains acting on the slide during forming was implemented. Using CAD models, a series of finite element analyses were run through Solidworks. Finite element analysis (FEA) was used due to the high level of detail it conveys including accuracy and reliability. From these finite element analysis simulations of the S3F and S4F slides, the optimum sensor placement location was determined for the strain link. The optimal position must exhibit strains within the measureable range of the strain link yet not large enough to damage or fatigue the strain link.

Figures 12A and 12B are screenshots of a Solidworks generated model of an S3F slide with a heat map representing the equivalent strains the particular area is experiencing under a force load of 1 ton. To create this model, a static load test was used to simulate the maximum force exerted on the slide when it forms a part. The bottom and inclined sides with green arrows are constrained with a roller contact so that the faces of those sides are constrained to that plane. Also, the pin slot in the left side of the slide is fully constrained. The simulated 1 ton force—

denoted by purple arrows—is applied evenly throughout the front face of the tool holder and the three bolt holes that clamp the tool to the slide. The simulation shows that the maximum equivalent strain for the original slide occurs in the stress concentration directly behind the tool holder. On the other hand, the largest area of greatest strain follows intuition and is generally greatest around the area of smallest cross sectional area in between the pin and rear of the tool holder. Since this is the greatest area of strain, it is ideal to place our sensor near this area to achieve the greatest accuracy.



Figures 12A & 12B: Top and bottom strain heat maps of an S3F slide under a 1 ton-force depicting high strain concentrations in the rear of the slide where strain gauge placement will be optimal.

Furthermore, Figure 13 below shows the heat map of the modified S3 slide to accommodate our final design with the bolt-on Wintriss strain gauge under identical constraints as the Figures 12A and 12B.

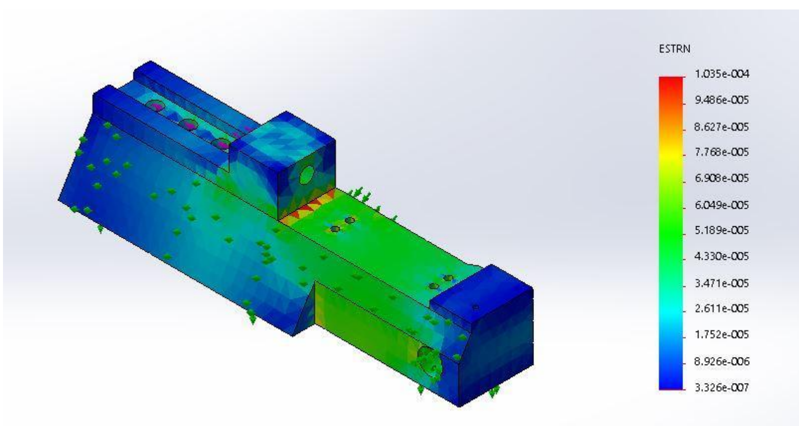
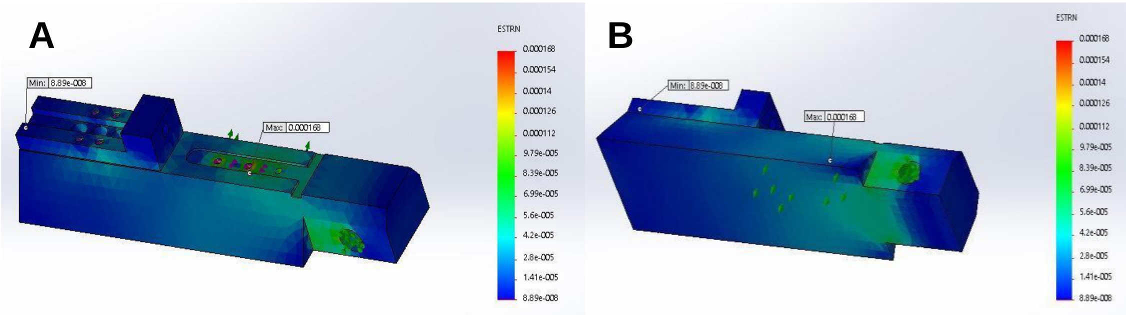


Figure 13: Isometric strain heat maps of the final S3F slide design under a 1 ton-force where the greatest strain is 103 microstrain.

Similarly, an FEA analysis was done for the S4F slide to show the equivalent strain heat maps under a 1.5 ton-force (Fig. 14A, & 14B). To create the S4F model, a static load test was used to simulate the maximum force exerted on the slide when it forms a part. The bottom and inclined side with green arrows are constrained to a roller so that the faces of those sides are constrained to that plane. Also, the pin slot in the left side of the slide is fully constrained. The simulated 1.5 ton-force--denoted by purple arrows--is applied evenly throughout the four bolt holes in which the particular tool is mounted. The greatest area of largest strain in the S4F slide also occurs between the pin and rear end of the tool holder.



Figures 14A & 14B: Strain heat maps depicting an S4F slide under a 1.5 ton-force. Although of smaller values than the S3F slide FEA, concentrations of strain are seen between the back of the tool holder and the pin, making this area ideal for strain gauge placement.

Mockup Modeling

The Wintriss sensor was chosen as the final design and a to-scale mockup was created to analyze multiple design drivers. When coupled with the S3F slide obtained from CCI, this mockup addressed the user requirement of scalability. The foam mockup was placed on top of the S3F slide (Figure 15) to assure that there was adequate room for the strain link to be secured. As the S3F slide has smaller dimensions than the S4F slide, it was used a basis for meeting scalability requirements.

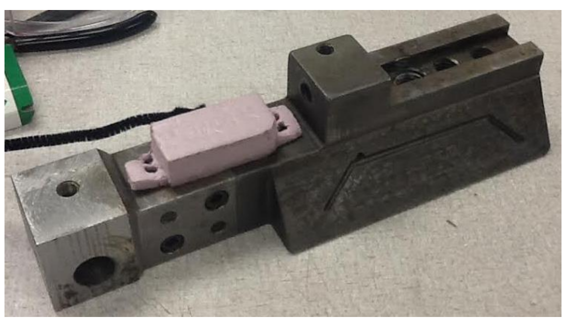
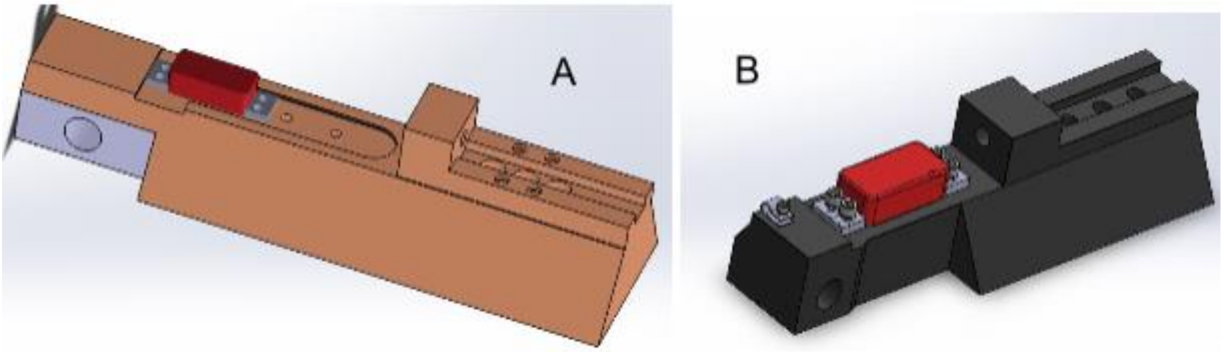


Figure 15: The foam mockup of the Wintriss strain link, to accurate dimensions, on top of a S3F slide.

CAD Modeling

To further examine the scalability of the S3F slide and to confirm the strain link scalability to the S4F slide, a series of Solidworks CAD models were created. The first CAD models were of the S3F and S4F slides with only the strain link and tooling as shown in Figure 16A and 16B. These CAD models both show that each slide has sufficient room to mount a Wintriss strain link on the rear end of the slide.



Figures 16A & 16B: Solidworks CAD screenshots of an S4F and S3F slide, respectively, showing the scalability of using a top-mounted Wintriss strain link.

After confirming scalability of the design, an S4F slide was examined with gas pack tooling. The use of gas pack tooling is dependent on the part being formed—specifically it is used when additional support is needed to hold the part in place as the forming process is completed. From this CAD model, a location was determined for the Wintriss strain link around which the gas pack tooling could be altered effectively so there was no interference with machine operation. As seen in on the final design, material was removed from a bottom section of the gas pack tooling (Figures 10A & 10B) and a pre-existing groove beneath the gas pack tooling was widened slightly to accommodate for the strain link. The original gas pack tooling was bolted to the slide with three bolts, however, in the new design the strain link will cover one of those bolt holes (Figure 17). The Solidworks CAD models confirm that the sensor fits and will not hinder the fourslide machine or gas pack tooling functionality in this location.

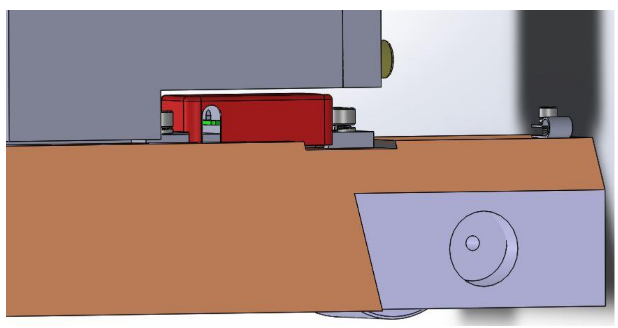
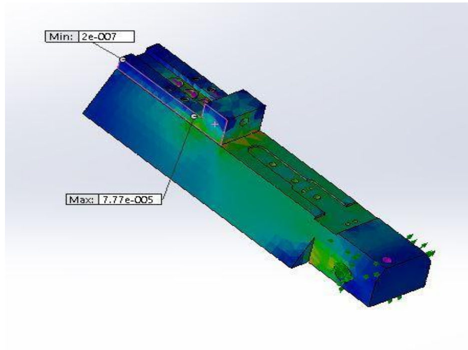


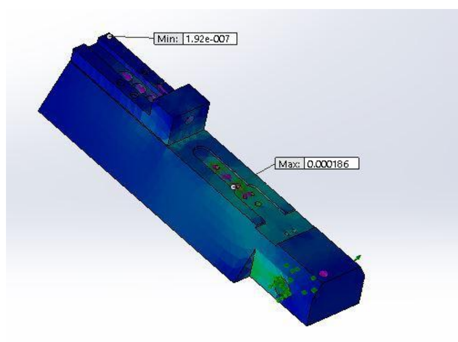
Figure 17: Side view of the strain gauge, slide, and redesigned gas pack tooling. Material was removed from the bottom section of the gas pack tooling to accommodate for the size of the Wintriss strain link.

Once a general placement of the strain link—between the tool holder and pin—was established from the S3F and S4F slide FEAs, we were able to use the CAD model and foam mockup, to finalize the strain link design. Using the FEA method, we performed an analysis with the new design. The Wintriss strain link requires relatively minimal machining to the slide including milling the top face to widen the pre-existing groove as well as drilling and tapping four holes. As a result of the minimal machining to the slide, the heat map depicting strain concentrations are relatively unchanged (Figure 18). This analysis highlighted the effect the slot and bolt hole changes will have on the strains the strain link will be measuring. It addresses the safety of the strain link, confirming that the new design fits within the limitations of the Wintriss strain link.



Figures 18: Isometric view of a strain heat map depicting the redesigned S4F slide under a 1.5 ton force without gas pack tooling.

Finally, to further address the placement of the strain link, FEA was run taking into account the gas pack tooling. This FEA includes a force applied to the two first gas pack bolt holes, simulating how the gas pack would be bolted in place when our design is applied. The inclusion of the gas pack into the FEA (Figure 19) took away strain concentrations towards the front end of the slide but added in more strain in the area that bolts the gas pack to the slide. As this is the area in which the Wintriss strain gauge will be placed. Supplementary simulations were run to determine the maximum forming force the sensor is capable of sustaining on an S4F slide with gas pack tooling present.



Figures 19: Isometric view of a strain heat map depicting the redesigned S4F slide under a 1.5 ton force with gas pack tooling. The gas pack tooling reduces strain concentrations at the front of the slide and results in higher strain concentrations behind the tool holder.

After completing an FEA of the redesigned S4F slide with gas pack tooling, there was an increase in strain in the region of strain link placement. To ensure that the strain link will be safely within its specified strain limits and to further understand the magnitude of changes in strain the slide will experience, a series of FEA simulations were ran on the redesigned S4F slide with gas pack tooling at differing applied tonnages.

The probe tool was used in Solidworks (Figure 20) to read the maximum and minimum strains that occur at the mounting locations. The results are shown in Table 1 (p.#) which clearly show that considerable strain is present in the region where the strain link is mounted. The Wintriss strain link has a capacity of 250 microstrain. From our results, we determined that it will be able to withstand a load of up to 7 tons applied to the S4F slide while gas pack tooling is in use. To mitigate strain gauge fatigue, the recommendation is to use a forming force of under 7 tons.

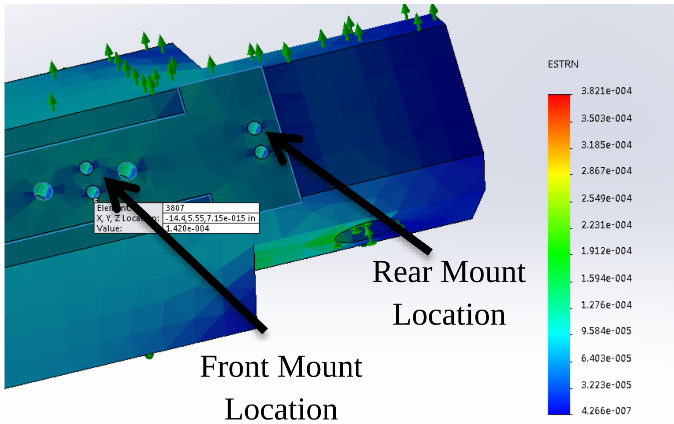


Figure 20: A strain heat map of an S4F slide at the strain gauge mounting location.

Table 3: Strains (microstrain) spanning the sensor location to validate sensor placement. The maximum safe tonnage before reducing the life of the strain link is 7 tons.

Force (tons)	Strain at Rear of Sensor (μstrain)	Strain at Front of Sensor (μstrain)
1	21	20
2	39	39
3	63	58
4	83	79
5	107	98
6	128	116
7	146	136
8	164	157

Fatigue Analysis

To address the safety of the machine, a max tonnage rating on the fourslide forming section has been established. The pin and bushing were designed to be the point of failure of the fourslide machine and have a history of failing due to fatigue. Therefore, fatigue analysis simulation in Solidworks has driven the determination of the max tonnage rating of the forming section of the fourslide machine.

The simulation consisted of the front slide, pin, bushing, and roller that is driven by the cam. In order to run a fatigue analysis, a static study was used at the moment at which the part was being formed. Within the static study, a no penetration contact was used between the slide and pin, and pin and bushing to restrain the bodies from penetrating each other during simulation. A bonded contact was chosen between the bushing and roller because the bushing is press fit into the roller. The roller-slider fixture was applied to the bottom and side faces of the slide which constrained them from translating out of the plane they reside in. The cylindrical face of the roller was fixed because at the moment of forming it is fixed within the cam. An external load was applied in the bolt holes used to mount the tool to the slide and the static simulation was run. Once this was done, fatigue analysis could be performed.

As part of the fatigue analysis, the Stress-Number of Cycles (SN) curves were defined for all the materials within the model. These gives the alternating stress required to cause failure at a given number of cycles of loading. Solidworks had a SN curve for grey cast iron, the material of which the slide consists. For the other three materials SN curves were found on CES Edu pack, a comprehensive materials database. For the cyclic loading, a repeated and reversed curve with a stress ratio of 0.1 (Figure 21) was used to emulate that the compressive stress as a result of forming is much greater than the tensile force used to translate the slide.

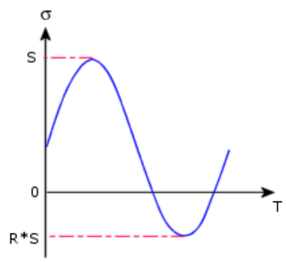


Figure 21: Loading curve used to emulate cyclic loading during machining with R=0.1 in simulations.

The simulation was run for 1E8 cycles the amount of cycles the SN curves listed and returned how many cycles each element in the model survived. The results when 6 tons was applied are shown in Figure 22. The bushing survives the least amount of cycles followed by the sharp edge of the slide directly above the pin and it was determined that the bushing is most susceptible to fatigue. The applied force was varied incrementally up to 9 tons, and below 4.5 tons every element survived the study without fatigue. The amount of cycles to failure for the bushing from forces ranging from 4.5 to 7 tons is plotted in Figure 23. As fatigue doesn't occur at loads less than 4.5 tons, failure due to fatigue can be eliminated by setting the max tonnage rating of the front slide at 4.5 tons. If the loads that are occur exceed the max tonnage rating, the provided data can be used to determine after how many cycles the bushings need to be switched out.

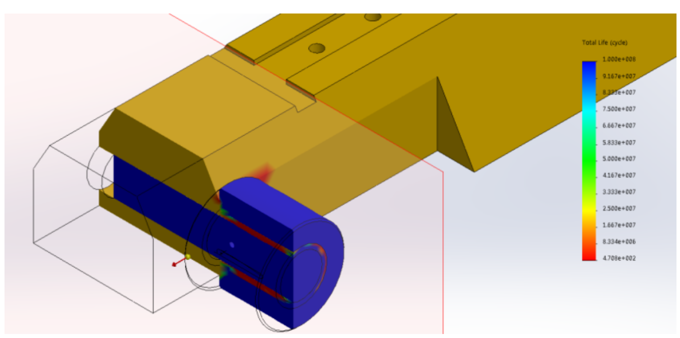


Figure 22: Resulting Plot of Fatigue Analysis at 6.25 tons that gives the cyclical life of different parts of the model.

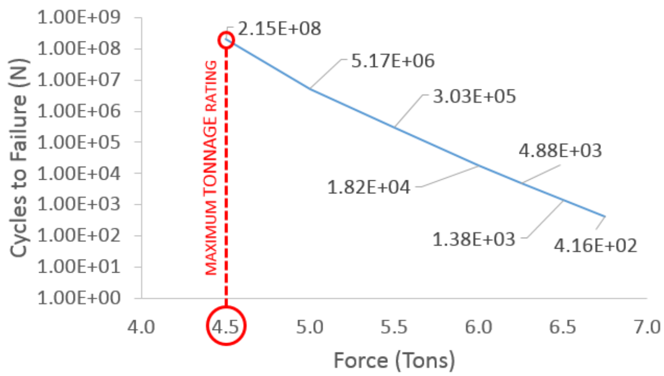


Figure 23: Plot of cycles to failure for the bushing at various applied loads.

To further the analysis of the max tonnage rating, the absolute max tonnage of the front slide was determined by finding the forming force required to cause plastic deformation. The same static simulations used in the fatigue analysis were used with forming forces ranging from 5 to 9 tons. The max stress within each component was recorded and compared against the respective yield stress of the component. It was determined that the bushing was once again the point of failure, as the yield strength of the bushing was 5% of the yield strength of the tool steels used in the pin and roller. The max stress within the bushing at each applied tonnage is shown in Figure 24. When 8 tons is applied, the max stress within the bushing exceeds its yield strength and plastic deformation occurs resulting in permanent damage. In conclusion, while the recommended max tonnage of 4.5 tons can be exceeded, it must be kept below 8 tons to prevent plastic deformation within the bushing that could cause significant damage to the machine.

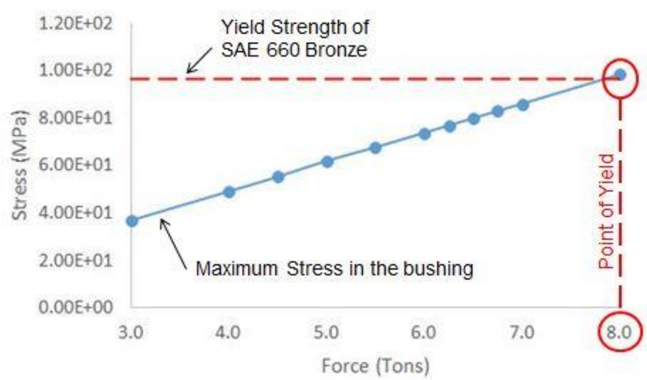


Figure 24: Plot of the max stress in the bushing vs tonnage applied. Shows that bushing will yield when just under 8 tons is applied during forming.

Section 9: Validation

In order to validate that the strain link design meets the requirements, a series of validation procedures were made and completed. Validation tests were performed in regards to machine scalability, accurate measurement of forming forces, automatic shutoff capability, and strain link and wiring safety so that they do not interfere with machine operation. Future work includes the validation of the theoretical models used to derive a maximum tonnage rating for the fourslide forming section through empirical testing and tracking of machine maintenance over time. The complete set of step-by-step validation testing plans can be found in Appendix H.

Firstly, machine scalability was validated though multiple methods including both CAD and physical models to ensure the Wintriss strain link fit within the size constraints of an S3F slide. These models are shown in figures 25A & 25B where the placement of the strain link is the same relative location as on the S4F slide. However, due to the size of the Wintriss strain link, an S3F slide would be unable to hold additional gas pack tooling.

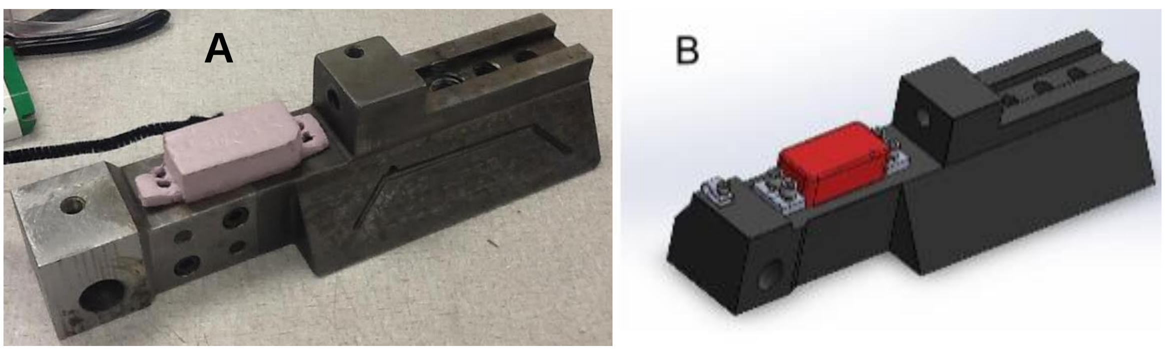


Figure 25A & 25B: The physical mock-up and CAD models both show that the top mounting of a Wintriss strain link is scalable to the smaller, S3F slide.

Furthermore, to ensure accuracy of the strain link, a calibration procedure was performed where a load cell was pressed between the front and rear slides (Figure 26). The readings from the strain link and the load cell were compared. After tuning the strain link, the output from the strain link was compared to the load cell output as shown in Figure 27A & 27B from which we see the tonnage of 3.3 tons on the SmartPAC monitor while the load cell output is 6,782lbs. More detailed information regarding the calibration process can be found in Appendix XX.

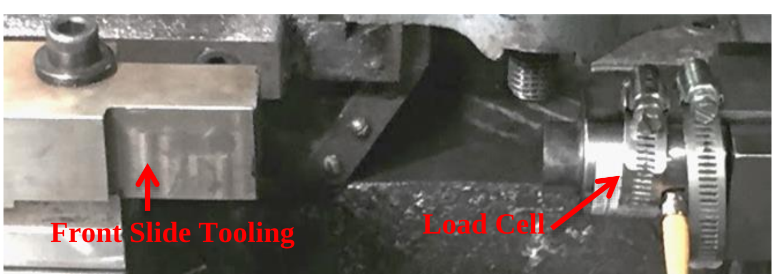


Figure 26: The setup for calibration of the strain link involving the compression of a load cell between the front and rear slides.

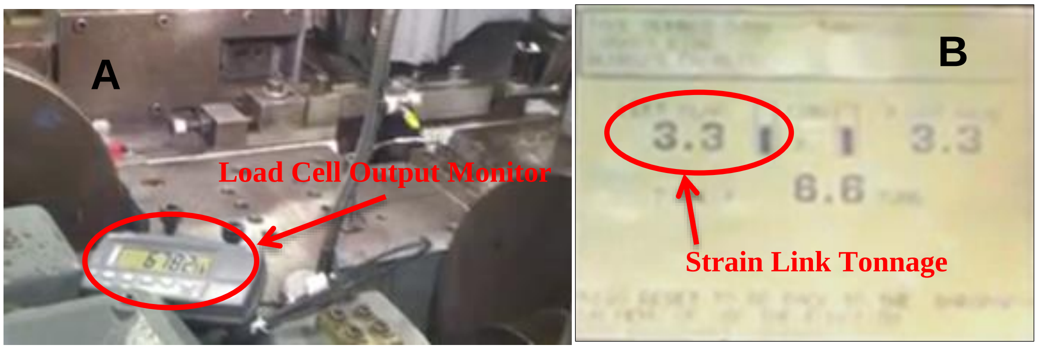


Figure 27A & 27B: After tuning of the strain link, the SmartPAC monitor showed consistent tonnage measurements with what was shown by the load cell monitor.

The output from the load cell was tracked from hit to hit which was used to determine the metal forming force process variability which was ±0.3 tons whereas the maximum resolution of the SmartPAC controller is ±0.1 tons. Thus, due to the process variability being so high from hit to hit operation, the Wintriss strain link is sufficient to track the tonnage of the metal forming forces in operation.

After the calibration of the strain link and verifying the accuracy of the tonnage readings, the next validation procedure involved the auto-shutoff capability. In order to test the auto-shutoff capability, a maximum tonnage limit was programmed in the SmartPAC controller at 5 tons and the machine was cycled through manually and in inch-mode. As seen in Figures 28A & 28B, the force displayed by the load cell monitor exceeds the tonnage limit in the SmartPAC resulting in the fault window on the SmartPAC monitor. A major fault such as this would stop the machine as quickly as touching the safety guarding around the fourslide or releasing one of the two push buttons required to start the machine in continuous mode.

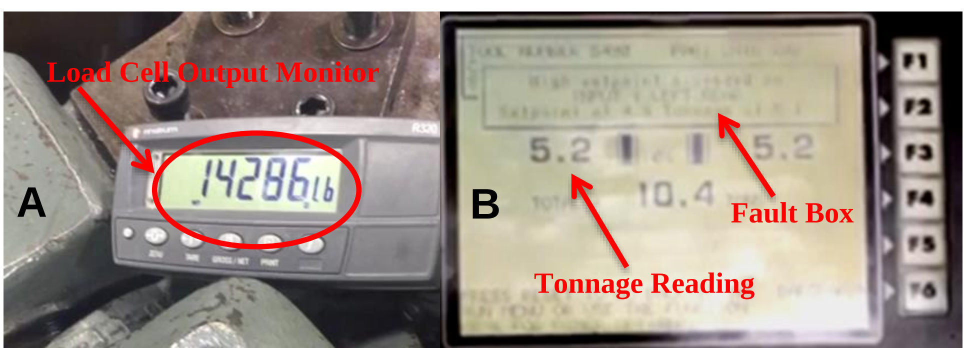


Figure XX: The programmed maximum tonnage limit was exceeded resulting in the fault box appearing on the SmartPAC which also automatically stops the machine.

In conjunction with the auto-shutoff capability, the maximum recommended tonnage rating determined through theoretical analysis that 4.5 tons is the maximum tonnage at which the machine is safe to run; running above the maximum recommended tonnage rating causes the pin and bushing to fatigue at an accelerated rate. The finite element and fatigue analysis models predict high stress concentrations in areas of the pin and bushing pointing to them as the most likely first points of failure. Based on several provided samples of broken pins and worn bushings from the machine exhibiting wear and fracture in the predicted areas of high stress concentrations, the theoretical models seem credible. Based on the models, the bushings are the first component to fatigue beginning at 4.5 tons and yield at 8 tons. As seen in Figures 29 & 30, the worn bushing allows for greater movement of the pin resulting in an accelerated rate of fatigue and causes more variability in the forming forces.

Figures 29 & 30: The fatigued bushing shown on the left shows significantly more wear than the new bushing on the right.

In addition to the worn bushing, two broken pins were provided which both exhibited the same characteristics of wear and failure as predicted by the fatigue analysis. Stress concentrations were greatest in the pin center at the interface of the slide and cam follower. As shown in Figure 31, the pin cross-section reveals fatigue via crack propagation near the interface of the slide and cam follower.

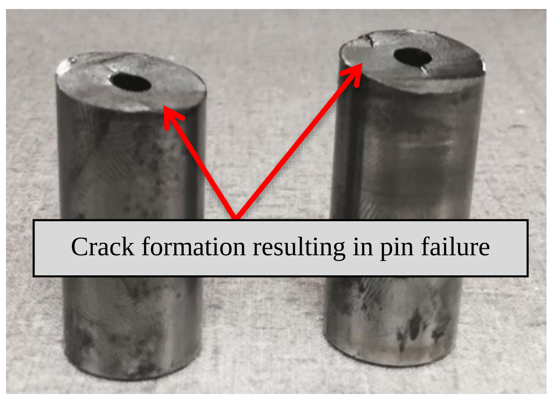


Figure 31: Fatigued Pin

Furthermore, through examination of an old slide, as shown in Figure 32, excessive wear was found around the periphery of the pin slot as well as deformation of the slot. This fatigue is also consistent with the simulation results shown in Figure 22, p.26.

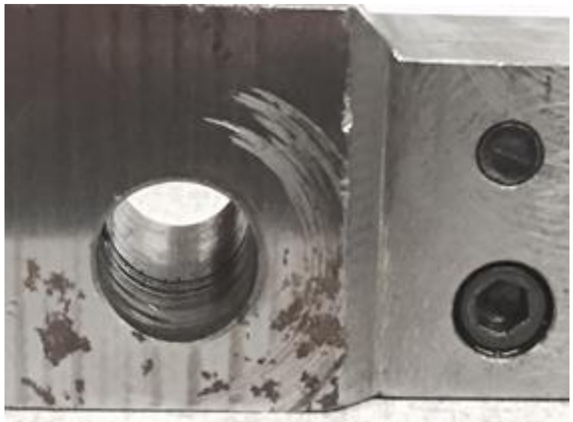


Figure 32: Fatigued slide

To further confirm the validity of the theoretical analysis and maximum tonnage rating, it must be validated empirically involving monitoring of the forming forces exerted by the fourslide machine and logging the replacement of the bushing, pin, and strain link— if necessary.

As for validating that the design does not interfere with routine machine operation and operator safety, the fourslide was ran in continuous mode for several minutes to simulate normal operation. No wires were exposed or snagging hazards evident and no hindrances to machine operation were observed.

Section 10: FMEA / Risk Analysis

There are a variety of factors that need to be taken into consideration whilst evaluating the safety of the design. The fourslide machine is a product-focused machine and the implementation of the design requires minimal human interaction. Therefore, a failure mode effect analysis was created to delve into the risk issues present with the machine and design itself.
As the failure mode effect analysis (Appendix F.1) highlights the parts of the design that could potentially cause failure are the strain gauge sensor, the wiring, and the bolts. Each of these parts have different ways that they could fail, and the FMEA takes into account the severity of effect if it failed, the probability of it failing within a year, and the probability of detecting it. These ratings are evaluated in order to create an overall RPN score; a higher score results in higher priority being placed on combating that mode of failure in the design process.

Through this analysis, it is clear that the potential failure mode with the highest risk is fatigue from cyclic loading within the wiring. Due to the high volume of parts that the fourslide machine creates, there are a lot of cycles that the machine undertakes, leading to a high probability that there will be failure from cyclic loading in the wiring due to fatigue. Failure will lead to no force reading to be transmitted as well and hence no idea whether the force limits are being exceeded and could lead to excessive damage of the machine, hence being a very serious effect. Detection is difficult as well and can only be realized after failure, and all these ratings lead to the highest RPN score of 192. Currently, the design control for the wiring is a strain relief wire holder being at the back of slide with the wires being glued in to a milled slot at the bottom end of the machine. Taking in to account the potential failure mode, there are wiring design changes in order to reduce the risk associated with it. These are reducing the amount of loose wiring, but at the same time making sure it isn't too tight. Furthermore, there will be no wires by sharp edges. Also, the safety shut off is not going to be dependent on the wiring. Though not a direct solution to the wiring problem, the autonomous shut off will be implemented if no load information is being recorded, hence minimizing any potential damages if the wiring is frayed, but the drawback is that it could lead to excessive delays. These design changes are placed in order to reduce the overall fatigue in the wires. They collaborate and aid to reduce the risk of failure by fatigue of the wires and it is as an acceptable level now as there is nothing else that can be implemented to reduce it even more.

Section 11: Discussion

Through the iterative nature of the design process, it is clear that there are a variety of ways in which we would have changed our design process in hindsight. First and foremost, our approach to the problem was naïve and disjointed at first, and only become concrete later on in the process. This is due to the fact that initially we focused on the mechanical design of the concept instead of the actual analysis of the forming process. Due to the user requirement of SmartPAC capability, there was an extremely limited amount of designs which could be viably implemented, and we spent an excessive amount of time researching techniques which would not be possible. The limited time left for analysis of the forming process caused our Finite Element Analysis (FEA) to be quite simplistic because we used Solidworks, which is not the ideal software for FEA, as well as not having enough time in order to take every variable such as friction in to account. Nevertheless, we are highly confident that our maximum tonnage rating of 4.5 tons is accurate, and recommend that CCI keeps their forces below that in order for no fatigue to occur. In order to refine the overall process, we would have spent a longer time on the FEA by taking into account more variables and constraints and hence getting the overall FEA to be as accurate as possible.

Another major change which would have improved the overall design of our concept would have been to not use the SmartPAC as the output monitor. To begin with, the SmartPAC only had a resolution of 0.1 tons, and though this is accurate in terms of getting a baseline maximum tonnage rating, it renders the accuracy of the sensor useless because it would only show forces to the nearest 0.1 tons. After extensive thought, it became clear to us that the SmartPAC is ideal for the press section of the fourslide due to the static nature of the process and higher forces, but is not ideal for the forming section. In addition, due to compatibility with the SmartPAC being one of the user requirements, it limited the whole scope of our design process because the only sensor which was compatible with it was the Wintriss strain link. This constrained our project by not being able to use other types of sensors and not having an extremely precise output monitor. To refine the whole design, we recommend that CCI does not limit the scope of the design by requiring SmartPAC capability, thus allowing us to analyze other sensors to view their functionality in comparison to our goals. Our recommendation would be to implement a DSF high endurance strain gauge instead behind the gas pack because it’s small size would allow us not to have to recess anything on either slide for scalability, hence not increasing strain concentrations. Furthermore, this adhesive strain gauge is made for a manufacturing setting and is rated high in fatigue cycling, making it ideal for our design.

Section 12: Information Sources & Reference List

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Appendix A: Specifications & Requirements

Wintriss AutoSet Load Analyzers

Equipment	**System Enclosure (all four models):** 10.25 x 12 x 4 in. (26 x 30.5 x 10.2 cm), NEMA 12, shock-mounted
	Panel Mount Option: 10.4 x 13.5 x 4 in. (26.4 x 34.3 x 10.2 cm)
Power	**Input:** 120/240 VAC ±15%, 50/60Hz, 15W for 1500, 30W for 1504
Inputs	**2 or 4 sensors:** 0 to ±0.1 V min - 2.5V max differential signal
	Zero cam (required for Plus models, optional for standard models): After the initial calibration, allows to re-zero after each stroke (the standard models can do this without external input if the tonnage exceeds 5% of press capacity only at the bottom of the stroke). Remote reset.
Outputs	**1 stop relay:** Rating 5A @ 120/240 VAC (N/O, held closed)
	Sensor excitation: 5 VDC
	Chart recorder: ±5 V Full Scale with respect to ground
Speed	**All models with zero cam:** up to 2,000 strokes per minute
	AutoSet 1500 without zero cam: up to 400 strokes per minute
Displays	**AutoSet 1500 series**
	Two 3-digit 0.43 in. (1.10 cm) for tonnages
	Two 3-digit 0.30 in. (0.76 cm) for setpoints
	Reverse tonnage views available on Plus models only
	AutoSet 1504 Plus
	Four 3-digit 0.43 in. (1.10 cm) for tonnages
	Four 3-digit 0.30 in. (0.76 cm) for setpoints
	One 4-digit 0.43 in. (1.10 cm) for total tons
	Reverse tonnage views available
Strain Links	**Product size:** 3.75 x 1.19 x 0.75 in. (9.5 x 3.0 x 1.9 cm)
	Cable length: 30 ft (9.1 m) standard or 100 ft (30.5 m). Hirschmann in-line connector available
	Excitation: 4 to 6 VDC
	Full scale signal: ±240 mV/V differential
	Full scale capacity: ±250 microstrain

Figure A.1: Specifications for Wintriss AutoSet Load Analyzers (Wintriss bolt-on Strain link)

Appendix B: Concept Generation

Brainstorming List

<u>Different Types of Force Transducers</u>

1. Bolted Strain Gauge Load Cell
2. Adhesive Strain Gauge Load Cell
3. Piezoelectric Crystal Force Transducer
4. Hydraulic Load Cell
5. Pneumatic Load Cell
6. Linear Variable Differential Transducer
7. Capacitive Load Cell
8. Magneto-elastic Force transducer
9. Interference-Optical Load Cell
10. Voltage Measurements from Engine

<u>Placements of Transducer</u>

1. Side of the the slide in counterbored pocket with protective covering
2. Bolted on Bottom of the slide inside a recess
3. Back of toolholder with cell housing
4. Front of toolholder where tool is placed with cell housing
5. On tool that allows for universal configuration where load cell can be easily removed from tool and placed on others
6. On Top of toolholder with cell housing

<u>Wire Configuration</u>

1. Wireless
2. Threaded under machine to smartpac with
3. Pliable plastic casing surrounding the wire and separating it from machine
4. Strain relief wire holder
5. Wire threaded through drilled hole in rear of slide
6. Quick disconnect for ease of maintenance
7. Milled slot that wire

<u>Added Safety Features</u>

1. Break-away tooling design
2. Break-away forming/centerpost
3. Bright Colours on the sensor
4. Plastic Box Around Sensor
5. Implement better lubrication system for pin-bushing
6. Digital readouts for consistent and speedier job setup
7. Monitoring
8. Improve lubrication system - higher pressure for more flow, more efficient lube
9. Shear pins in cam
10. Shear pins in beginning of shaft near electric drive motor

<u>Different Types of Analysis</u>

1. Contact companies who have listed tonnage ratings on forming machines to gain insight in the steps they used to rate the tonnage capabilities of the machine
2. Free Body Diagram
    a. Bushings vs. Bearings for load pin
    b. Bushings / Bearing analysis for those on shaft
    c. Shaft deflection analysis
3. Adams simulation
4. FEA using Hyperworks on all components that make the slide
5. Compare forces on different parts(failure, almost failure, smooth running) and create safety factor

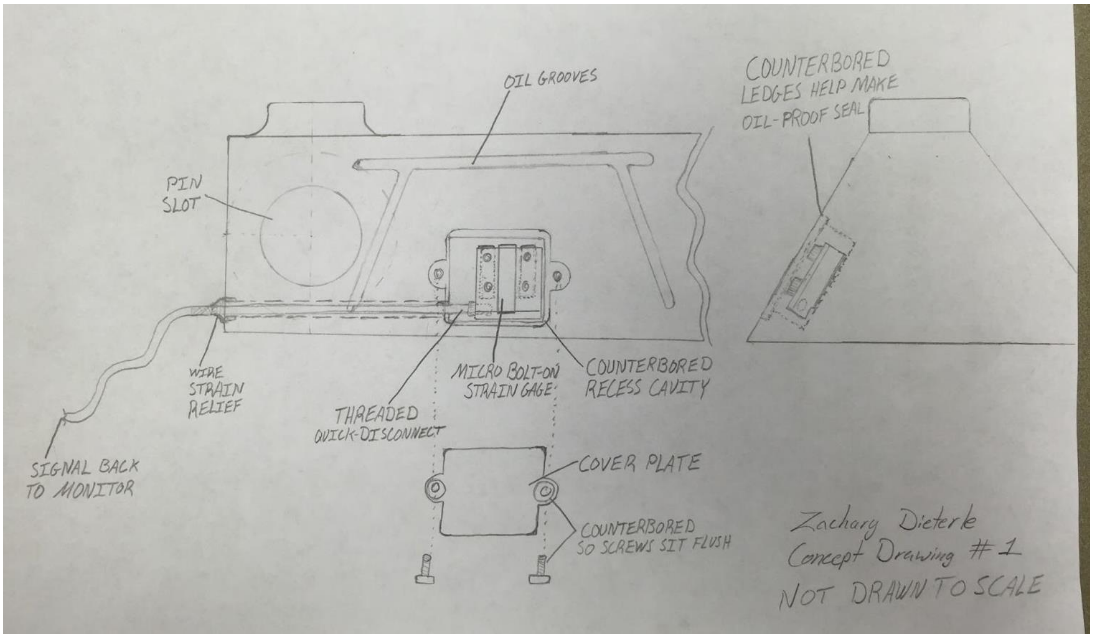


Figure B.1: Concept One: Bolt on strain gauge on side of slide

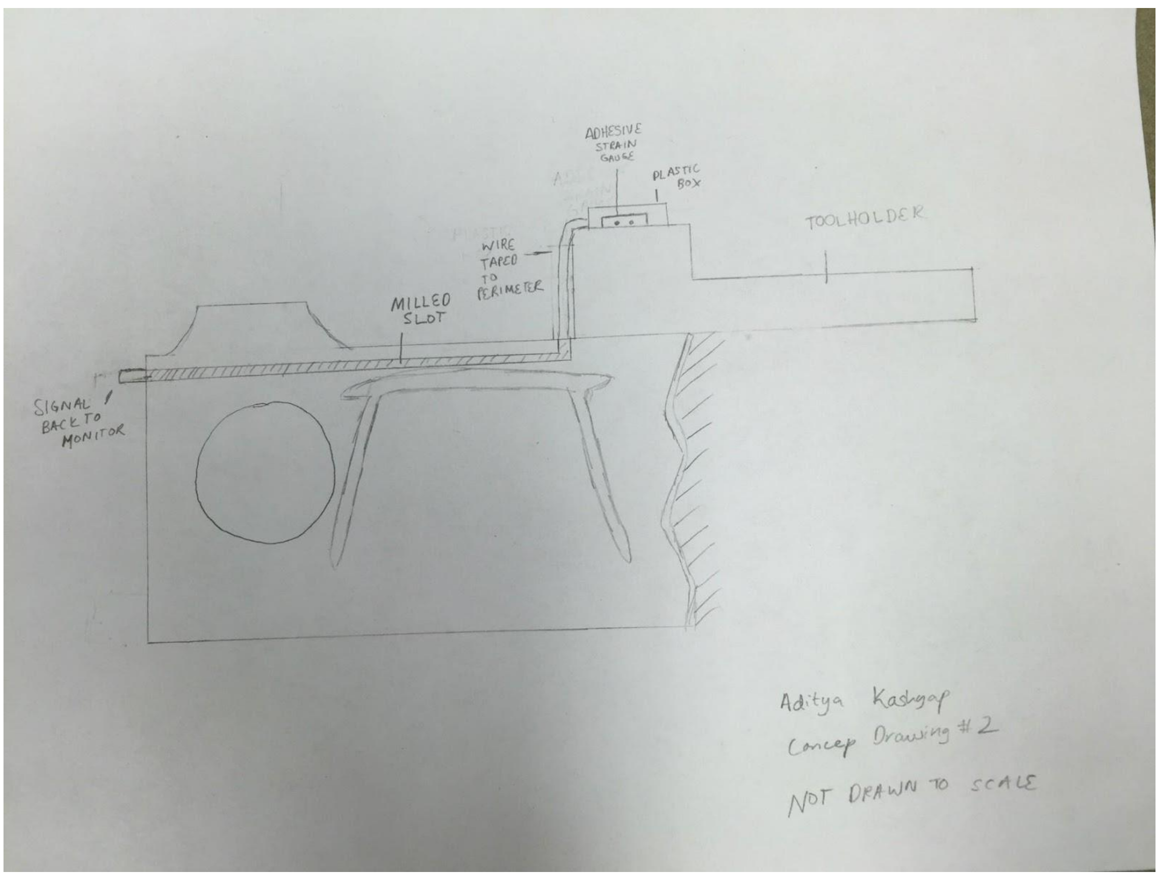


Figure B.2: Concept Two: Adhesive strain gauge mounted on tool holder

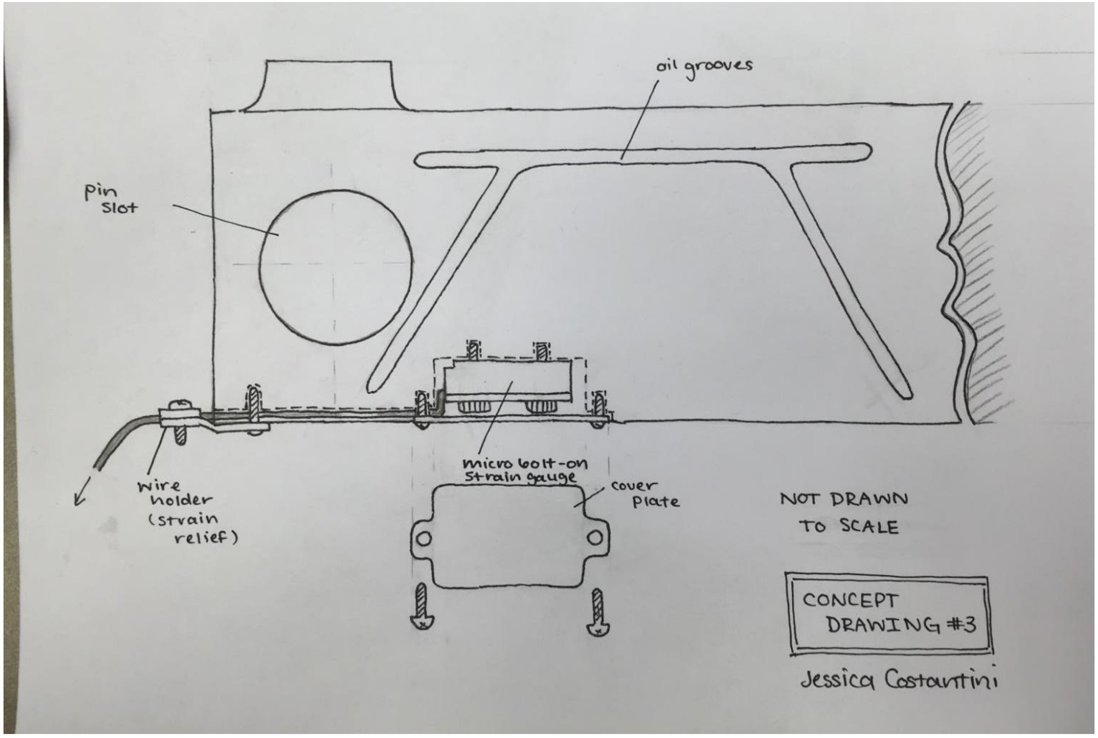


Figure B.3: Concept Three: Bolt on strain gauge mounted on the bottom of the slide

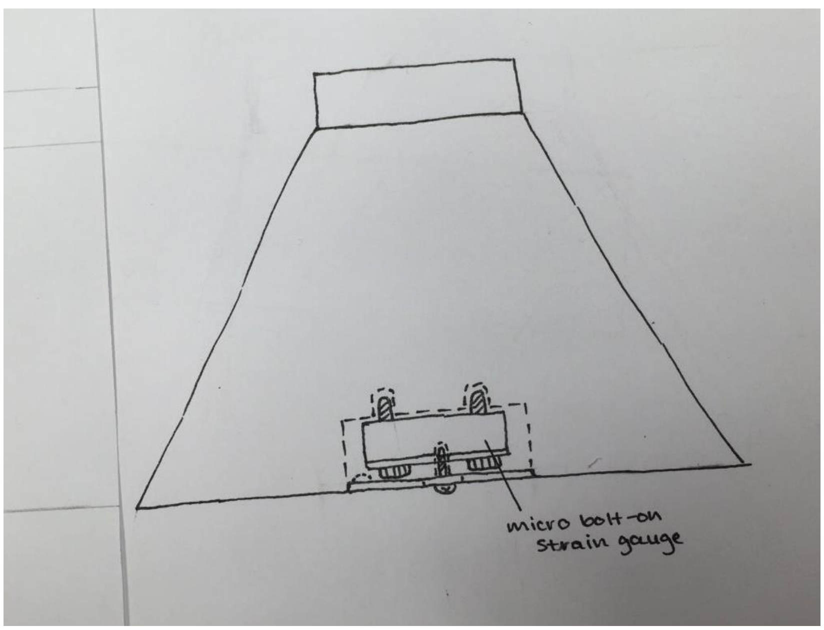


Figure B.4: Concept Three Side View

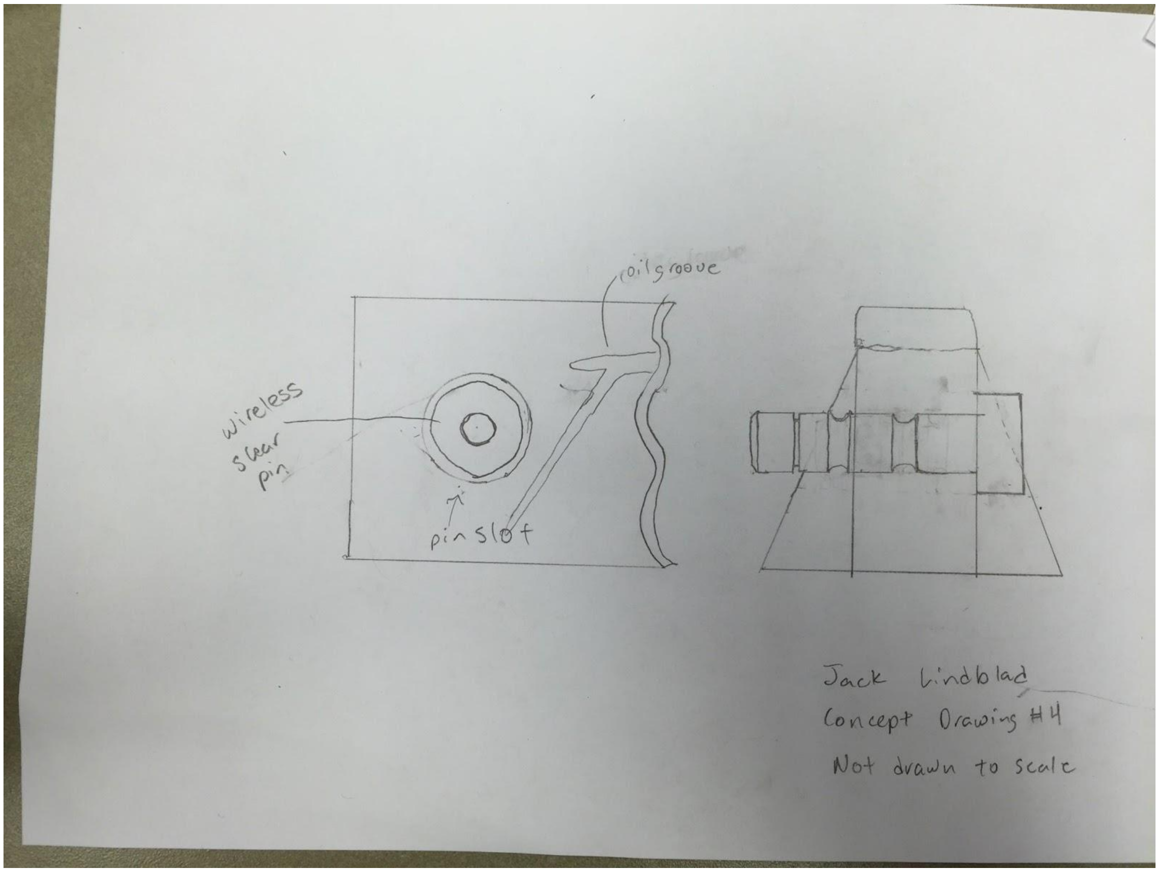


Figure B.5: Concept Four: Wireless Shear pin used in slide/cam joint

Appendix C: Concept Selection Matrices

Table C.1: Pugh Chart for Force Measurement

Selection Criteria	Weight of Criteria From 1 to 3	Shear Pin Replacing Bushing	Voltage Measurements From Engine	Strain Gauge Load Cell	Piezoelectric Crystal Force Transducer	Hydraulic Load Cell	Linear Variable Differential Transducer	Capacitive Load Cell	Pneumatic Load Cell
Frequency of Response	3	6	1	6	6	0	6	5	0
Scalability of Measurement System	3	6	6	6	6	2	2	5	2
Provides Part Quality Control	3	4	1	6	6	0	6	3	0
Cost Effectiveness	1	0	6	4	2	3	1	5	3
Total		16	14	22	20	5	15	18	5
Weighted Total		48	30	58	56	9	43	44	9

Table C.2: Pugh Chart for Force Measurement Mount

Selection Criteria	Weight of Criteria From 1 to 3	Sensor Set Into Side Slide Notch with Protective Cover	Sensor Mounted on Tooling with Cell Housing	Sensor Mounted on Tool Holder with Cell Housing	Sensor Mounted to Tool in a Removable Way	Sensor Mounted to the Pin and Bushing	Sensor Mounted to Center Post	Sensor Mounted to Bottom of Slide	Sensor Mounted to Top of Slide
Provides Quality Control	3	5	6	5	6	4	1	5	5
Scalability of Measurement System	3	5	1	1	1	6	1	5	1
No Hindrance to Slide Machine	3	4	5	5	5	0	0	5	4
Ease of Maintenance	3	2	5	5	6	0	0	2	6
Ease of Manufacturability	2	3	4	4	1	0	0	4	5
Cost Effectiveness	1	6	0	0	6	6	2	6	6
Total		25	21	20	25	16	4	27	27
Weighted Total		60	59	56	62	36	8	65	64

Table C.3: Pugh Chart for Force Measurement

Selection Criteria	Weight of Criteria From 1 to 3	Break Away Tooling	Break Away Bushing	Electrical Automatic Max Tonnage Shut-off	Replace Bushing with Bearings	Shear Pin in Cam Shaft	Shear Pins in Beginning of Shaft By Motor	Break Away Center Post
Ease of Manufacturability	3	1	4	6	5	5	5	3
Responsiveness	3	6	6	6	3	6	1	3
Total		7	10	12	8	11	6	6
Weighted Total		21	30	36	24	33	18	18

Table C.4: Pugh Chart for Force Measurement

Selection Criteria	Weight of Criteria From 1 to 3	Wireless	Pliable Plastic Casing Surrounding the Wire	Milled Slot for Wire	Wire Threaded Through Drilled Hole in Rear of Slide
Ease of Manufacturability	3	6	5	4	2
Durability	2	5	3	6	6
Cost Effectiveness	1	0	5	6	6
Total		11	13	16	14
Weighted Total		28	26	30	24

Appendix D: Alternative Concepts

Concept #2: Top Mounted Adhesive Strain Gauge

Further research on available sensor options revealed an adhesive sensor alternative to the bolt-on sensor. This adhesive sensor, the DSF series high endurance strain gauge, is smaller in size and is rated higher in fatigue cycling. The smaller size of the sensor would allow it to be located on top of the slide; this limited space could not accommodate a bolt-on strain gauge. If the sensor is located on top of the slides, a recessed cavity will not be necessary, and therefore there will be no danger of increasing the strain concentrations. The adhesive DSF series high endurance strain gauge is made for a manufacturing setting and is rated high in fatigue cycling.

The design includes the adhesive DSF series high endurance strain gauge, placed on top of the slide in a groove. This positioning has an optimal input of forces from the slide. The groove the strain gauge would be placed in already exists on slides that have been outfitted for gas cylinders. The adhesive strain gauge would not interfere with the placement of the gas cylinder (Figure D.1).

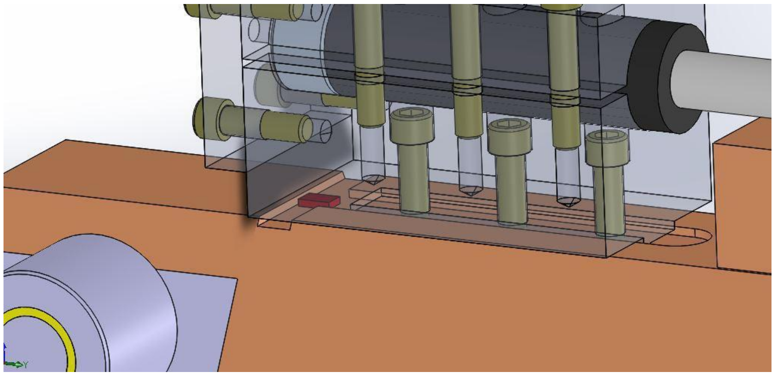


Figure D.1: The chosen strain gauge placement is denoted by a red box, to scale. The sensor is on top of the slide, in a groove underneath the gas cylinder.

The adhesive high endurance strain gauge would be an ideal product; however, it poses a few issues. Due to the small size of the sensor, the signal outputs would be small (mV). In order to make these values significant enough for the SmartPAC to read them, we would need to build an amplifier circuit for the strain gauge signals. Although the circuitry for an amplifier is relatively simple, it would need to be packaged durably to withstand the manufacturing environment. Also, transmitting small signals from the sensor through the wiring to the amplifier and SmartPAC setup would introduce significant noise. Because of this significant noise factor, we have decided to consider the adhesive strain gauge as our secondary design.

Concept #3: Bottom Mounted, Recessed Bolt-on Strain Link

The strain gauge load sensor will be mounted in a recessed cavity on the bottom of the front slide. A cover plate will be used to protect the sensor from damage and oil during operation. The recessed cavity, however, has been shifted further from the pin to an area of the slide with greater surface area (Figure D.2). This movement of the cavity is an attempt to protect the pin area from a greater concentration of stress, as this area is where failure is occurring. Our engineering analysis confirms this location is valid as it shows that strains are produced in this region to use for force measurement and that our sensor design fits within the size constraints of the surrounding machinery in this region. However, the high strains and stresses induced by milling out a cavity in the slide may lead to sensor failure due to fatigue. This design is not optimal for any additional tooling configuration that is mounted behind the tool holder. The sensor would essentially be blind to the forces acting on the additional tooling thus allowing the machine to exceed the maximum set tonnage.

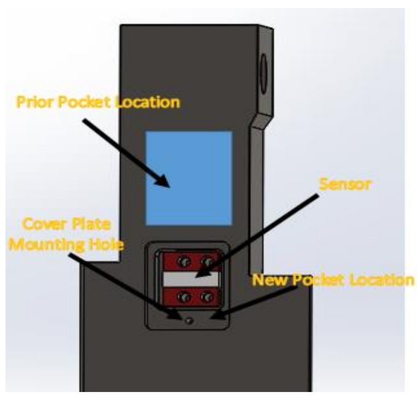


Figure D.2: Bottom view of a CAD model showing change in sensor and cavity location.

The FEAs displayed high strain concentrations caused by the recessed cavity, particularly in the corners of the cavity, and the sensor bolt holes (Figure D.3). Due to the lack of knowing the exact forces being exerted on the forming section of the fourslide, we are unable to accurately predict whether the strains seen in the FEA heat maps will be large enough to be an issue for sensor fatigue. There is concern, however, that removing this material and adding stress to the slides will increase the likelihood of fatigue failure of the slide itself.

Additionally, FEA analyses including a gas cylinder attached to the back of the slide showed that placing a sensor in the cavity beneath our slide would not capture all of the forces applied on the slide. The forces applied by the cylinder would not be read by the strain gauge. Although the gas cylinder is not included on all slides, it is used to give the machine extra support to make high-force parts. It is therefore important to have a design compatible with the gas cylinder and to monitor these specific parts with our force sensor, as these parts are more likely to lead to machine failure.

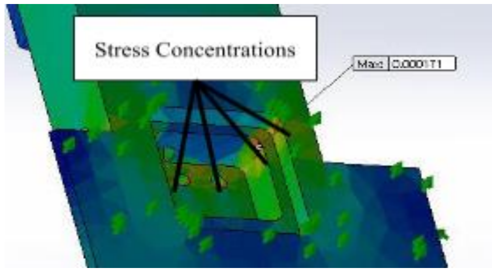


Figure D.3: High stress concentrations in the recessed cavity are denoted in red. They can be seen in the corners of the cavity and along the bolt holes for the strain gauge. The maximum strain on the FEA modeled slide is found in the corner of the recessed cavity.

Due to recent revelations of the SmartPAC specifications, we have found that this and the sensor we chose from Toledo Integrated Systems are not compatible. The TT40 sensor has an excitation voltage of 12V while the SmartPAC can only provide 5V. Therefore, our design will contain a new sensor. We have identified other strain gauges that will fit the current size constraints of the slide and are in the process of receiving the full list of SmartPAC specifications so that we may determine a compatible match.

Another change in our design is in the wiring configuration that allows the connection of the sensor to the SmartPAC. In our concept in design review 2, we had milled slot on the bottom of the slide that fed the wire from the pocket out of the back of the slide. We have changed the configuration to avoid causing stress concentrations beneath the pin. We also found from our mock up construction that this wiring method was not valid with the constraints of the surrounding machinery. Instead, a hole will be drilled on the flat portion of the side of the slide to connect to the counter bored pocket that houses the sensor (Figure D.4). The location of our pocket was driven by this hole, because our engineering analysis showed the hole had to be on the flat and not the angled portion of the slide. Due to this new wiring configuration, we added a cable gland to our design that can fasten into the tapped hole the wiring is fed out of. The cable gland will provide strain relief to the wiring but will more importantly insulate the counter bored pocket and prevent oil from getting in.

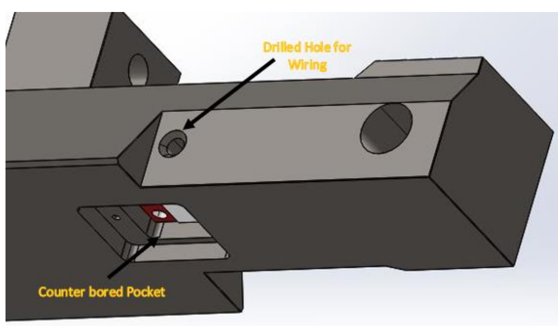


Figure D.4: Screenshot of Solidworks CAD model

Appendix E: Concept Finite Element Analysis

Table E.1: Strain readings (microstrain) spanning the sensor location to validate sensor placement.

		Strain (microstrain)			
Force (tons)	**Force (kN)**	**Minimum**	**Maximum**	**Rear of Sensor**	**Front of Sensor**
1	9.8	7	36	21	20
2	19.6	13	71	39	39
3	29.4	20	107	63	58
4	39.2	27	142	83	79
5	49.0	32	177	107	98
6	58.8	50	213	128	116
7	68.6	47	249	146	136
8	78.5	53	284	164	157

Appendix F: FMEA / Risk Analysis

Item	Function	Potential Failure Mode	Potential Effects of Failure	Severity of Effect	Potential Causes of Failure	Occur within year	Current Design Controls	Detection	RPN	Recommended Action
Strain Gage Sensor	Provides readings in the form of electrical signals directly proportional to the force being exerted through the slide	Oil covering sensor	Incorrect forces being shown, not accurate reading of actual forces of machine	7	Cover tolerances too high and strain gauge recess fills with oil. Seal between milled wire slot and strain gauge recess fails.	9	Counter-bored around strain gauge recessed cavity.	1	63	Insert a seal between the milled wire slot and the strain gauge recessed cavity.
		Incorrect mounting/ installation	Incorrect forces being shown, not accurate reading of actual forces of machine	7	Not proper installation of the sensor	3	Holes drilled into slide that fit sensor one way.	1	21	None.
		Non-optimal sensor placement	Sensor placed in location yielding subpar readings. Ultimately cannot be used as a means of process control and/or a reliable safety E-stop	9	Sensor not mounted in area of maximum compression, hence it doesn't correctly gauge the actual forces being exerted. Not screwed in all the way.Not placed in area where forces are actually being exerted	1	Finite element analysis on possible sensor placement.	6	54	
		Resolution too low	Incorrect forces being shown, not accurate reading of actual forces of machine	9	Incorrect straing gauge specifications.	1	Choose a sensor with high resolution, analysis to estimate required resolution.	1	9	Test sensor resolution to verify the listed specification.
		Noise from other sources	Incorrect forces being shown, not accurate reading of actual forces of machine	4	Incorrect force readings being conveyed as the noises from other machines are considered as fourslide's hence a higher force is shown	10	Noise cancelling is built into the strain gauge sensor choosen.	1	40	None.
		Calibration	Incorrect forces being shown, not accurate reading of actual forces acting on slide	6	Incorrect technique used. Load cell used is not accurate.	3	None.	3	54	Research steps to correctly calibrate a strain gauge sensor.
		Overheating	No force reading transmitted and no safety e-shut-off	7	Forces on surrounding machine components overheat. Strain gauge recessed cavity is too insulating	1	None.	1	7	Choose the cover plate material to not be very insulative. Do analysis on how much heat the strain gauge will produce; may be negligible.
		Short Circuit	No force reading transmitted and no safety e-shut-off	7	Wiring become stripped.	2	Use of strain reliefs, deburring of all sharp edges, and gluing wire into the milled wire slot.	1	14	Implement wire strain relief/secure wire in strain gauge recessed cavity. If not fesible, consider threading the wire through a drilled hole rather than along a milled slot.
Wiring	Provides a pathway for the electrical signals generated by the strain gage to reach a controller that has the ability to stop the machine.	Fatigue from cyclic loading	No force reading transmitted and no safety e-shut-off	8	Normal machine movement. Too much strain on wiring. No strain relief on wiring.	4	Using a strain relief wire holder at back of slide/end of milled wire slot. Gluing wire into milled wire slot.	6	192	Reduce the amount of loose wiring. No wires by sharp edges. Make sure wiring isn't too tight.
		Catching on nearby objects	No force reading transmitted and no safety e-shut-off	8	Loose wiring. No wire guide or cover. Lack of detection of wires.	3	Use of a wire strain relief on the rear of the slide as well as guiding the wire through the safety pipe surrounding the perimeter of the machine back to the controller panel.	1	24	Reduce the amount of loose wiring.
Bolts	Provides a means to secure the bolt-on strain gage to the surface of the slide as well as the cover plate to protect the sensor.	Overigntening	Damages circuitry of the sensor either breaking it or throwing off the calibration so it is unable to accurately read the forces on the slide	3	Operator applies too much torque to bolts damaging the sensor	7	Use lock washers and a torque wrench set to the recommended 76 ft*lbs for our chosen sensor	9	189	None.
		Loosening over time	Strain gage sensor loses contact with the surface of the slide resulting in inaccurate readings	3	Cyclic Loading, not tightened enough, no adhesive used, no lock washers used	9	Use lock washers	3	81	Use a nonpermanent thread adhesive.

Figure F.1: Failure Modes and Effects Analysis

Hazard	Hazardous Situation	Likelihood	Impact	Level	Technical Performance	Schedule	Cost	Action to Minimize Hazard
Electric Shock	When installing or performing maintenence on the device, the operator could be shocked as a result of frayed or open wires.	Low	Moderate	2	Minimal to Significant reduction in technical performance of the sensor because the shock may be caused by the operator's finger creating a short that otherwise wouldn't have affected the sensor. On the other hand, the short may ruin the circuity of the sensor rendering it unable to fulfil its purpose.	Little lasting effect on production schedule. Slip <1 week	Minimal or no impact	Add a strain relief wire holder to prevent unnecessary forces on the wires that may cause fraying. Do not leave wires hanging, secure them with a cover or slot. Have no open wires showing, use a threaded connector.
Wires Catching on nearby objects	While in operation, the wires from the back end of the slide may protrude far enough to catch onto nearby objects such as an operator	Medium	Minor	1	Significant reduction in technical peformance because the snagging of the wires is very likely to damage the functionality of the sensor.	No lasting effect on production schedule. Slip <1 day	Minimal or no impact	Have all wires secured to best of ability using strain reliefs and no unnecessry loose wires. Use a wire guide to contain wires.
Cut	When installing or performing maintenence on the device, the operator could be cut as a result of sharp edges or burrs left on the counterbored slot or sensor cover.	Low	Minor	1	Minimal or no degredation to technical performance	Minimal or no impact	Minimal or no impact	De-burr all edges with a file.
Sensor Cover/Cover Bolts Projectile	The sensor cover may come loose due to the cyclic motion and loosening of the bolts holding it in place. If the cover is in the section of the slide going into the pocket of the machine, it could become wedged between the machine and slide resulting in shearing of the bolts and/or cover plate.	Medium	Serious	4	Significant reduction in technical peformance because the deformation of the cover plate may damage the sensor and subsequemtly allow oils to reach the sensor.	Critical effect on production schedule (worst case). Slip <2 months if the machine is still usable.	Budget increase or unit cost increase >5%	Implement routine maintenance on sensor bolts. Use lock washers. Possible use of a non-permanent adhesive.
Fire	When there is oil present in the milled slot due and it interacts with frayed wires it could lead to a fire hazard	Low	Serious	4	Renders the sensor useless and can lead the machine to be unusable. Productivity falls for an extended period of time	Critical effect on production schedule (worst case). Slip <2 months if the machine is still usable	Budget increase or unit cost increase >5%	Constant monitoring of wires by making sure they are secured and covered throughout. May add a protective rubber covering to the wires
Strain Relief Wire Holder	The strain relief wire holder protrudes from the back of the slide and may act as a pinch point.	Low	Minor	1	Minimal to significant reduction in sensor performance. The wire strain relief can fail without immediately affecting the sensor. However, over time the wire may begin to experience fatigue resulting in the failure of the sensor	Minimal or no impact	Minimal or no impact	Add a guard around the strain relief wire holder, position it so that it is less likely to be in danger of catching items/fingers, or use a different type of strain relief wire holder.

Figure F.2: Risk Analysis of the recessed cavity design

Appendix G: Engineering Fabrication Plans

Engineering Drawings

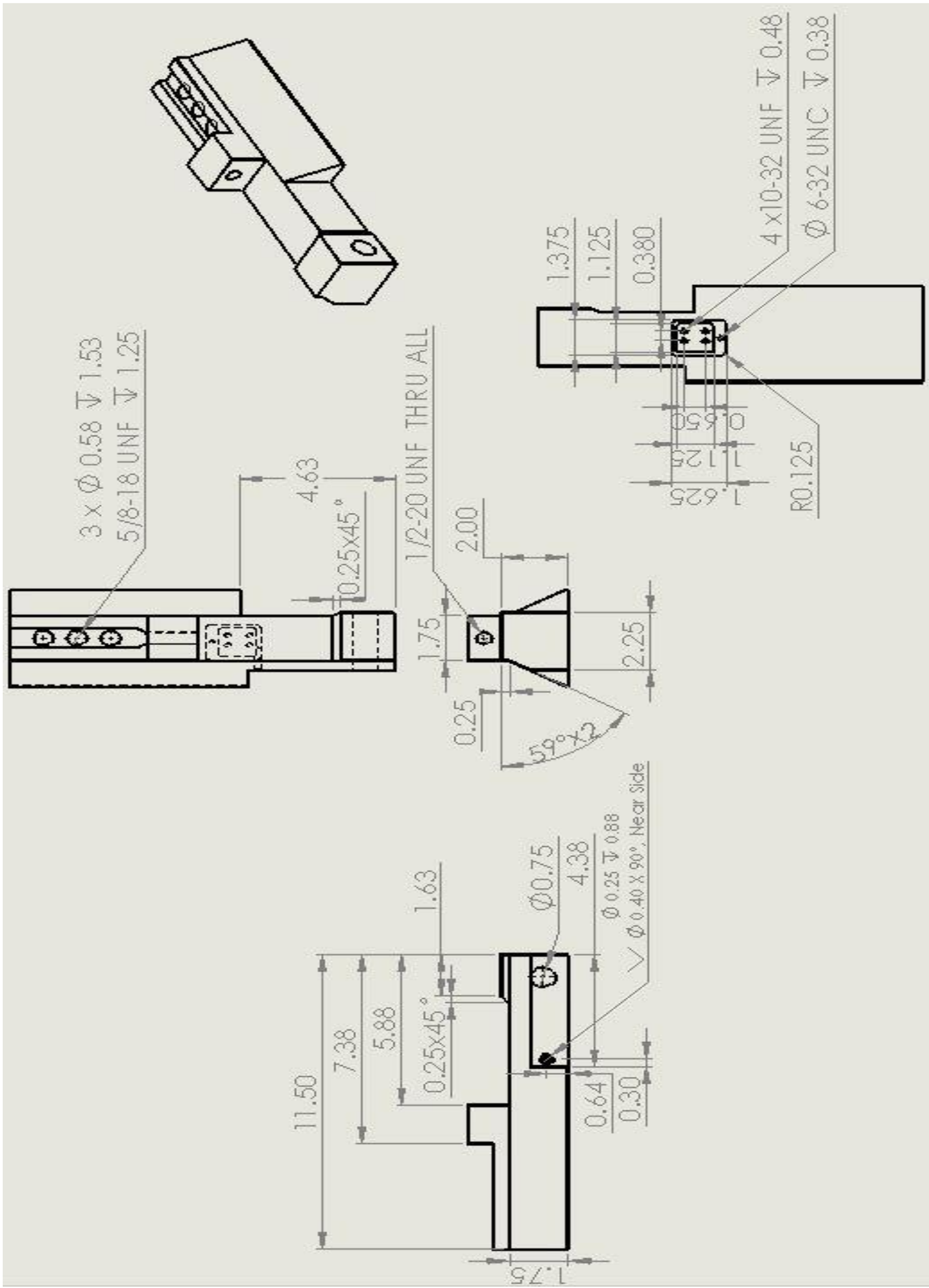


Figure G.1: Dimensioned CAD drawing of an S3 slide with recessed cavity, Design #3.

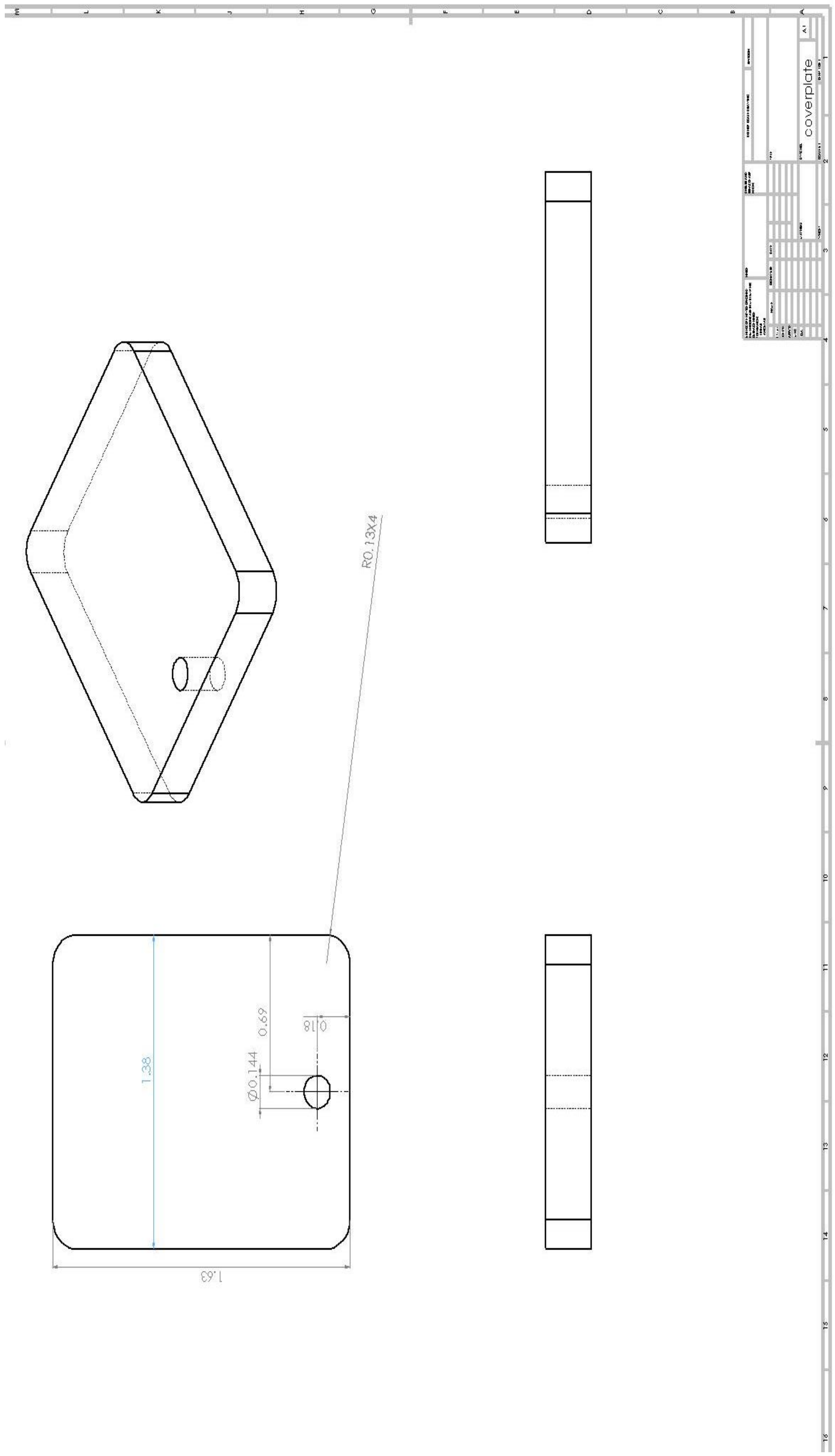


Figure G.2: Dimensioned CAD drawing of cover plate for recessed cavity.

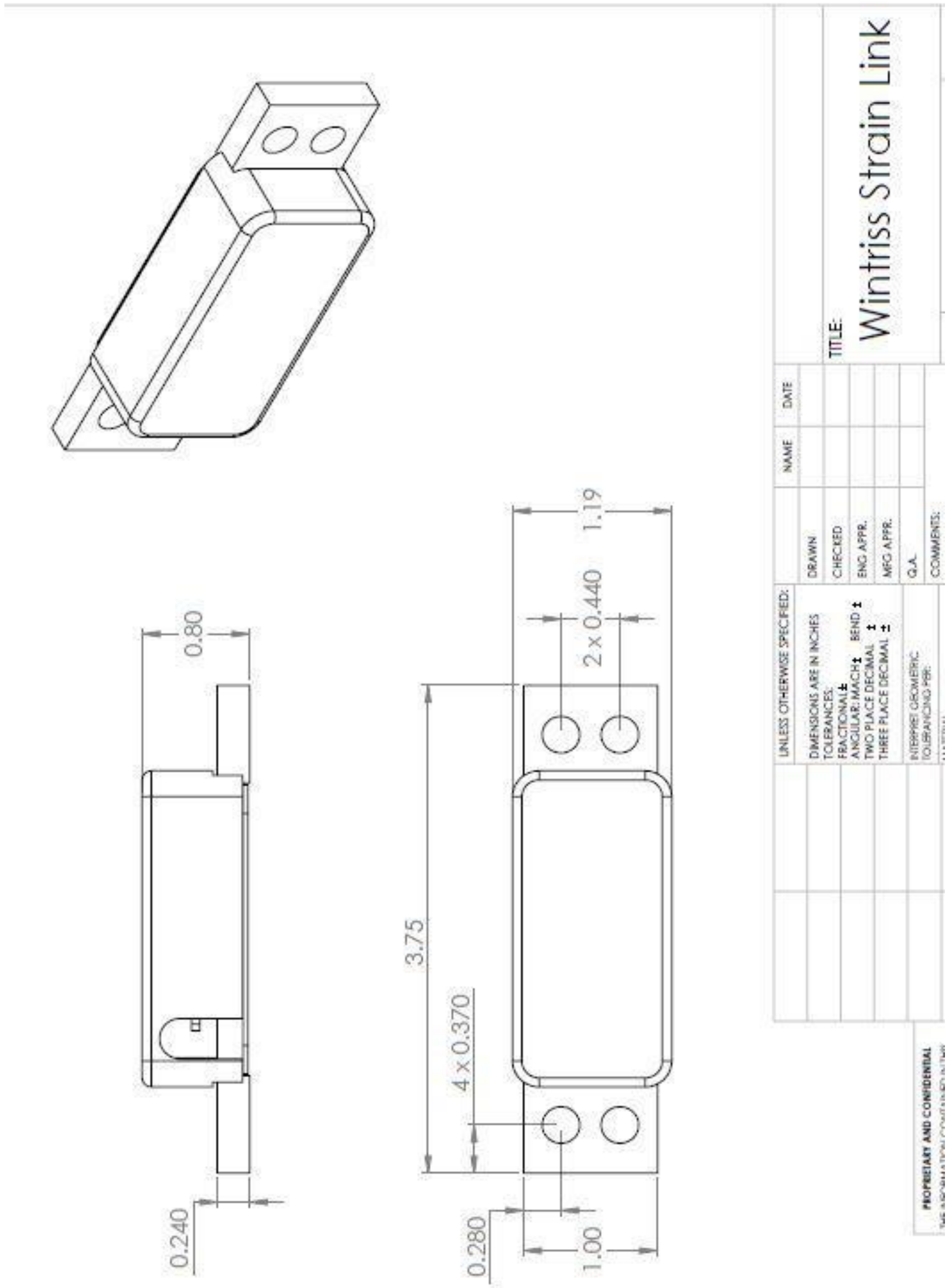


Figure G.3: Dimensioned CAD drawing of Wintriss Strain Link.

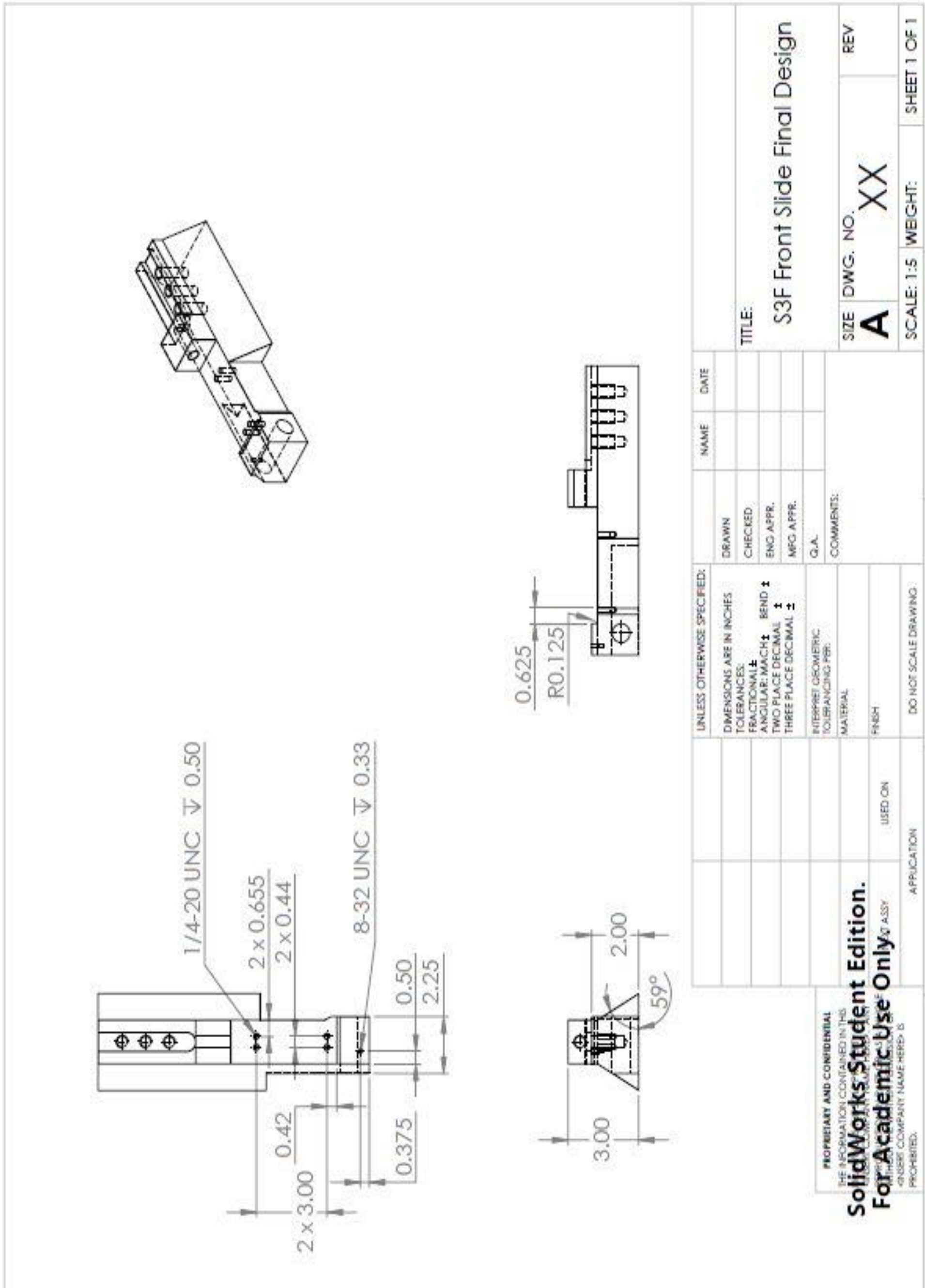


Figure G.5: Dimensioned CAD drawing of the final modified S3F slide with Wintriss bolt-on strain link and wire strain relief clamp mounts.

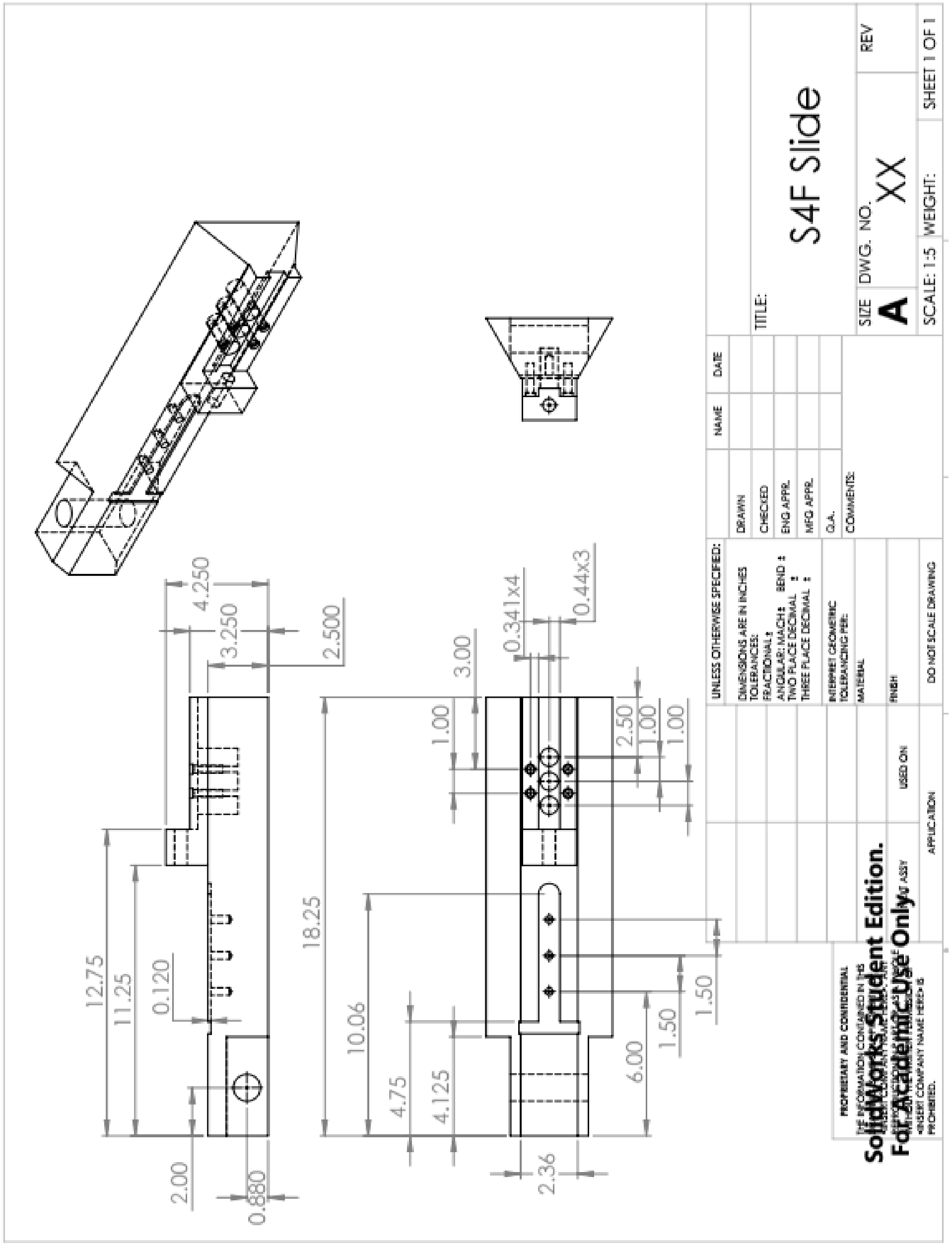


Figure G.6: Dimensioned CAD drawing of an original S4F slide.

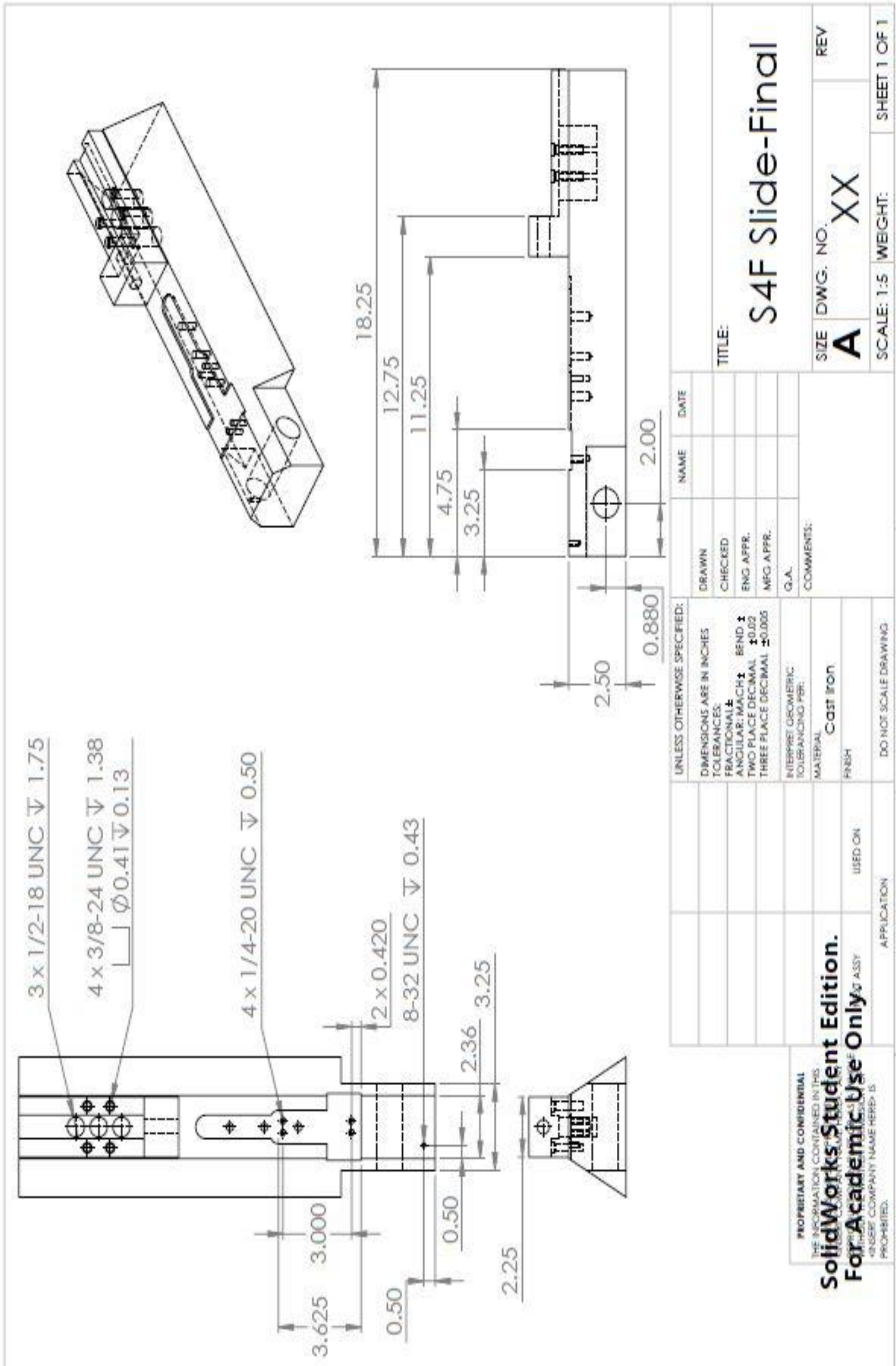


Figure G.7: Dimensioned CAD drawing of the final modified S4F slide with Wintriss bolt-on strain link and wire strain relief mounts.

Manufacturing Plans

Table G.1: Manufacturing plan for mounting Wintriss strain link on top of slide.

Revision Date: 11/8/2015

Part Number: ME450-001
Part Name: Front Slide

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Hold part in vise	Mill	Vise		
2	Find datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
3	Extend the milled slot by 1”	Mill	Vise	.25” end mill	1400
4	Widen the milled slot from ⅞’’ to 1 ¼”	Mill	Vise	.25” end mill	1400
5	Find datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
6	Drill 4 .25” holes to a depth of 3/4”	Mill	Vise	#7 drill bit	1600
7	Tap the four holes	Mill	Vise	¼-20 Tap and handle	

Table G.2: Manufacturing plan for Design #3: recessed cavity in the front slide.

Revision Date: 10/23/2015

Part Number: ME450-001
Part Name: Front Slide

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Hold part in vise	Mill	Vise		
2	Find datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
3	End mill the 1.63" by 1.38" pocket to a depth of .25"	Mill	Vise	.25" end mill	1400
4	End mill the 1.13" by 1.13" pocket to a depth of .74"	Mill	Vise	#25 drill bit for 10-24, #38 drill bit, drill chuck	600
5	Find datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
6	Drill the .1065" hole to a depth of .54"	Mill	Vise	#36 drill bit	1600
7	Tap the hole		Vise	6-32 tap and handle	
8	Drill the four .1590 holes to a depth of 1.39"	Mill	Vise	#21 drill bit	1400
9	Tap the four holes	Mill	Vise	10-32 Tap and handle	
10	Find the datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
11	Drill the .25" clearance hole to a depth of .88"	Mill	Vise	F drill bit	1200

Table G.3: Manufacturing plan for the cover plate covering the recessed cavity.

Revision Date: 10/23/2015

Part Number: ME450-002
Part Name: Cover Plate

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Wire EDM the part contour	Wire EDM			
2	Find datum lines for X and Y	Mill	Vise	Edge finder, drill chuck	800
3	Drill the .144” clearance hole through the face	Mill	Vise	#27 drill bit	1400

Bill of Materials

Table G.4: A bill of materials for the recessed cavity design, Design #3.

ITEM NO.	PART NAME	MATERIAL	SUPPLIER	PART NUMBER	PRICE ($)	QTY
1	TT40 MICRO LOAD SENSOR		TOLEDO INTEGRATED SYSTEMS	TT40	N/A	1
2	6-32 3/4’ STEEL CAP SCREW	GRADE 8 STEEL	MCMASTER - CARR	92620A406	11.50	1
3	10-32 1’ STEEL CAP SCREW	GRADE 8 STEEL	MCMASTER - CARR	92620A418	12.25	4
4	¼’’ THICK 6’’ WIDE 1 FT LONG- TIGHT TOLERANCE FLAT GROUND	A2 TOOL STEEL	MCMASTER-CARR	9019K47	11.10	1
5	THOMAS & BETTS NON METALLIC LIQUID TIGHT CABLE CORD GRIPS	NYLON	CALCO	CC-NPT-34-B	2.96	1

Table G.5: A bill of materials for the final design.

ITEM NO.	PART NAME	MATERIAL	SUPPLIER	PART NUMBER	PRICE ($)	QTY
1	Wintriss Strain Link		Wintriss		360	1

Appendix H: Validation Testing Plans

Table H.1: Maximum Tonnage Rating Validation Plan

Step #	Task
1	No empirical way to validate without driving the fourslide machine to failure.

Table H.2: Sensor & Wiring Lifetime Validation Testing Plan

Step #	Task
1	Create a log and place it near the sensor.
2	Log the amount of time and approximate number of machine cycles for which the sensor and wiring produce optimal output before either needs maintenance or needs to be replaced.

Table H.3: Correct Measurement of Forces Validation Testing Plan

Step #	Task
1	Calibrated sensor is mounted in the machine and producing a signal output.
2	Load cell is attached between center post and slide tooling.
3	Move tooling until it is pressed against the center post.
4	Record signal output of the load cell and of the strain gauge.
5	Compare the output of the load cell with the strain gauge output signal.
6	Repeat above steps for a series of forces.

Table H.4: Machine Safety Validation Testing Plan

Step #	Task
1	Calibrated sensor is mounted in the machine and producing a signal output.
2	Run the machine for a part, record the force signature produced.
3	Choose a low tonnage value based on the empirical data from step 2 that the machine will reach while running the part.

4	Specify this value in the SmartPAC interface as a tonnage that should shut off the machine if it is exceeded.
5	Run the fourslide machine.
6	Record the force signature of the sensor output as the parts are produced. If the specified tonnage is reached, the machine should shut off.

Table H.5: Operator Safety Validation Plan

Step #	Task
1	Create a log and place it near the sensor.
2	Log any potential hazards caused by the sensor and wiring over the lifetime of the product.
3	Correct any potential safety hazards.

Table H.6: Sensor Safety Validation Plan

Step #	Task
1	Calibrated strain gauge is mounted on the machine and producing a signal output.
2	Run fourslide machine forming process.
3	Record maximum force signal output from sensor.
4	Compare this value to the maximum sensor rating of 7 tons.

This validation plan will test the strains the sensor will experience to ensure that they are low enough to not cause failure of the sensor. This has been partially validated through fatigue analysis and strain gauge specifications; the sensor will experience failure at a force on the slide of over 7 tons. This validation is redundant as the recommended maximum tonnage rating is set at 4.5 tons, and therefore the fourslide machine will shut off automatically well below the point of failure of the strain gauge. However, this will be validated redundantly to ensure that the machine is indeed not reaching these forces while running normal parts.

Table H.7: Scalability Validation Plan

Step #	Task
1	Implement strain gauge design on a S3F fourslide machine.

Scalability has already been validated through CAD models and measurements of the slides and strain gauge. It will not be officially validated until it has been implemented on the smaller S3F slide, however.

Table H.8: No Interference with Machine Operation Validation Plan

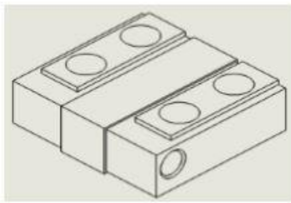
Step #	Task
1	Operate the fourslide machine while the strain gauge is in use.

No interference with fourslide machine operation has been partially validated through modeling the fourslide machine in Solidworks, mock-up modeling, and machine and strain gauge measurements. It will not be completely validated, however, until operation of the machine with the strain gauge design implemented. Part of this validation includes the maximum tonnage rating set high enough that it does not greatly hinder the fourslide machine forming parts.

Appendix I: Engineering Changes

Figure I.1: Engineering Change Notice 1

WAS:



TT40 Strain Link Load Cell

IS:

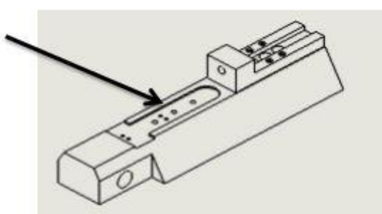
Wintriss Strain Link

Note:
Needed to replace TT40 Strain Link with Wintriss Strain Link to satisfy compatability requirements with a SmartPAC controller.

Team 17		
Project:	Fourslide Metal Forming	
Ref Drawing:	TT-40 & Wintriss Strain Link	
Engineer:	Jack Lindblad	11/1/2015
Proj. Mgr:	Zach Dieterle	11/3/2015
Mgmt./Sponsor:	CCI	11/3/2015

Figure I.2: Engineering Change Notice 2

WAS:



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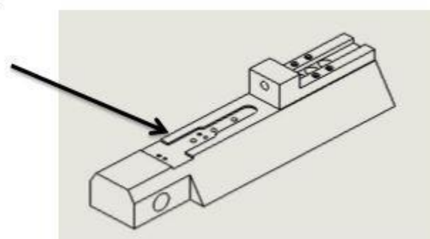
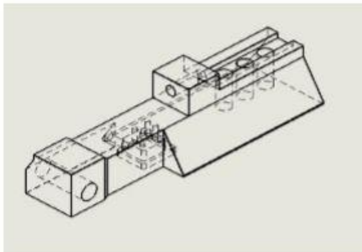


Note:
The milled groove on the top face was shortened to accommodate the Wintriss sensor and so the narrower groove may still act as a guide slot for an additional tooling gas pack.

Team 17		
Project:	Fourslide Metal Forming	
Ref Drawing:	S4F Front Slide	
Engineer:	Zach Dieterle	19-Nov
Proj. Mgr:	Zach Dieterle	19-Nov
Mgmt./Sponsor:	CCI	21-Nov

Figure I.3: Engineering Change Notice 3

WAS:



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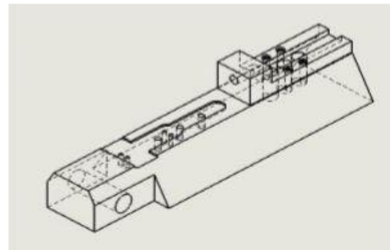
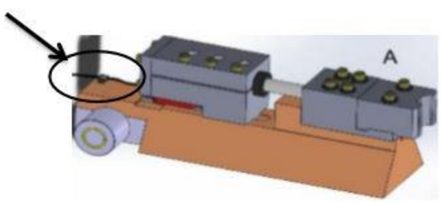


Note:
Due to the change to use a larger, Wintriss sensor, it was necessary to mount on the top of the slide.

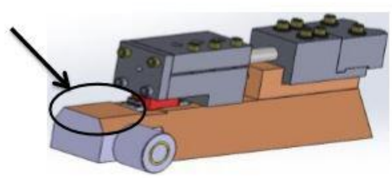
Team 17		
Project:	Fourslide Metal Forming	
Ref Drawing:	S4F Slide Final	
Engineer:	Zach Dieterle	10-Nov
Proj. Mgr:	Zach Dieterle	10-Nov
Mgmt./Sponsor:	CCI	15-Nov

Figure I.4: Engineering Change Notice 4

WAS:



IS:



Notes:
Removed wire strain relief for a second option of running the wiring out beneath the slide. This allows for the wiring to be more out of the way and uses less unnecessary parts. The slide itself works as strain relief.

Team 17		
Project:	Fourslide Metal Forming	
Ref Drawing:	S4F Front Slide	
Engineer:	Zach Dieterle	30-Nov
Proj. Mgr:	Zach Dieterle	30-Nov
Mgmt./Sponsor:	CCI	30-Nov

Appendix O: Ethical Design Statement

The Code of Ethics has been utilized throughout our design in various ways including mitigating the cost to the sponsor, efficient use of time, and a keen attention to ensuring safety. Firstly, we iterated through multiple designs and through the use of an FMEA determined the most critical safety aspects associated with each design. One of the designs in particular, had the potential to be much more dangerous such that the bolts used to fasten it were located underneath the slide which requires removal of the slide to perform maintenance on the strain link. As a result, this design was set to a lower priority and was not used as the final design. Furthermore, the final design concept we used includes a sensor compatible with the existing technology used by our sponsor which in turn, saves the sponsor money, requires less time to implement, and allows for more effective use of time to create the final design. Additionally, the compatibility and scalability of the final design allows for shop-wide integration with minimal loss in production and initial investment.

Authors

Zachary Dieterle

A senior in Mechanical Engineering at the University of Michigan with an anticipated graduation in the spring of 2016. Upon graduation, he plans to pursue a career in the field of industrial automation. In addition to scholastic and endeavors, he is a competing member of the U of M Club Wrestling team.

Jessica Costantini

A senior in Mechanical Engineering at the University of Michigan, Jessica will be graduating in December of 2015. She is interested in manufacturing and sustainability. In her free time, she enjoys reading and learning to swing dance.

Jack Lindblad

A senior in Mechanical Engineering at the University of Michigan. Jack was born in London, where he lived until he was two years old and moved to Chicago. Jack is an avid sports fan, and loves play and watch sports. He was raised a University of Michigan sports fan and became die-hard fan. Jack loves to play golf and has spent the last nine summers caddying at a golf course.

Adi Kashyap

A senior in Mechanical Engineering at the University of Michigan, Adi will be graduating in April 2016. Adi is from Singapore and has lived in six different places throughout his life. He enjoys squash, cognitive psychology, and classical music. In the future, Adi would like to pursue his interests in structural integrity and manufacturing in the automotive industry.

Acknowledgements

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