

Industrial Paper Tray

“Is That All You’ve Got?!?”

Lexmark Group #3

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I. Introduction

Paper trays used by Lexmark encounter problems caused from different types of loading due to the environments they are in and from user abuse. This project involves studying how the paper trays react to forces and finding ways to make the trays stand up to extreme abuse. Objectives of the project include identifying high stress areas of the tray, identifying and analyzing the loads that the tray experiences, and designing and testing solutions to help minimize failure in the tray.

The tray that we are redesigning is the 250-Sheet Tray that is used in the MS71x and MS81x family of printers. The new industrial tray for this model only has to be used in the A4 and US Letter paper sizes. The budget for this project allows \$20 per tray at manufacturing cost.

Some of the loads the tray experiences during use include slamming, torsional loading, rotational loading, and dropping. Areas that are prone to failure as stated by Lexmark include the front face plate, the rails on either side of the tray, and the rear restraint.

Success for this project involves analyzing the tray through cyclic loading, assorted forces, and drops. From this data there should be sufficient results to formulate ideas to help design reinforcements for the tray. A successful tray would be able to stand up to abuse from a user including cyclic loading ($\geq 100,000$ cycles), high impact paper tray slams (≥ 150 cycles), side collisions, torsional collisions (being sat on while extended until printer is lifted from table), and impact with the ground.

II. Hypothesis

Before beginning our test, areas of failure were identified so that they could be observed during failure. These areas of failure were determined from input from Lexmark and through team predictions. These failure modes and other points of interest can be

seen in Figure 1. Areas that were identified as failure modes by Lexmark were the tray rails and the rear restraint (Figure 1 (a)). Our team predictions also identified these areas along with predictions of general damage of the tray exterior from being repeatedly dropped by the user.

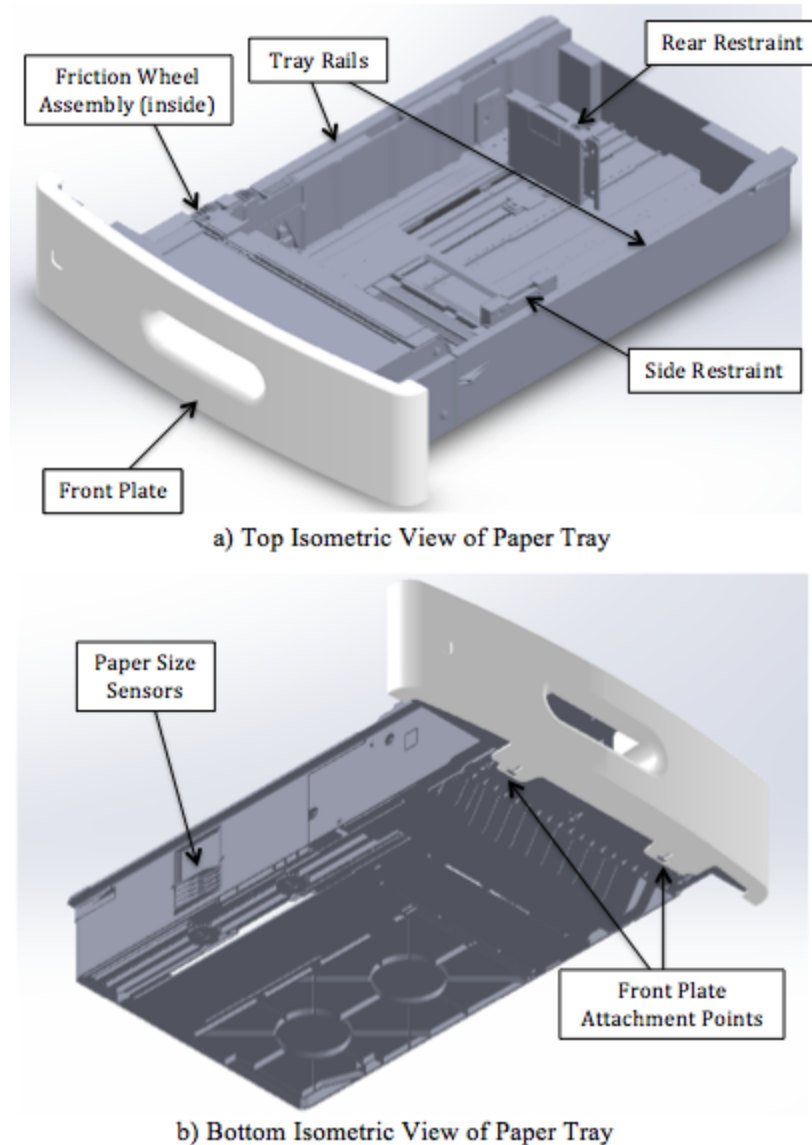


Figure 1. Parts of Interest in the 250 Page Paper Tray

We predicted the tray rails received their damage from being inserted and extracted over multiple cycles with a heavy slam from the user. We also predicted that

these rails would break when under torsional loading and side loading. From these loads, we expected a larger force to be exerted on these rails when paper was in the tray.

The rear restraint is what holds the paper in place from the back during use. We predicted that this rear restraint would fail by bending from high impact paper tray slams. This was a failure mode that was discussed with Lexmark because they had received customer complaints about the rear restraint bending after use. We also predicted that the rear restraint would move back with high impact paper tray slams from the large force the restraint would encounter. Both of these failures would cause the rear restraint to lose its functionality.

Drop damage can cause catastrophic failure to the tray in multiple areas. We expected the attachment points on the front plate (Figure 1 (b)) of the paper tray to fail in addition to general damage to the tray from repeated collisions with the ground. With these areas noted, they were observed closely during testing to see how they failed. More areas experienced failure than were initially predicted and they too were addressed in our design process.

III. Testing of Hypothesis

A. Empirical Testing

i) Drop Test Experiment

Introduction

When the paper tray collides with the ground, the impact can cause damage to the part. The tray experiences a larger acceleration as it tries to rapidly slow down, which can cause great amounts of stress on areas of the paper tray. In order to prevent failure of the tray after a collision with the ground, we needed to test by repeatedly dropping it so we could understand all of the ways in which it could fail.

Test Procedure

For the drop test experiment, the tray was held from table height (36" - 48") and dropped flat. An accelerometer was placed at different locations on the tray based on predicted failure areas. These locations consisted of two locations in the front, one location on the rear paper restraint and two locations on the back of the paper tray (Figures 2 and 3). Readings for the acceleration at these points were taken by using an amplifier and were then processed by SCOPE. The SCOPE software took samples of the acceleration every 0.001 seconds which allowed us to find the peak acceleration.

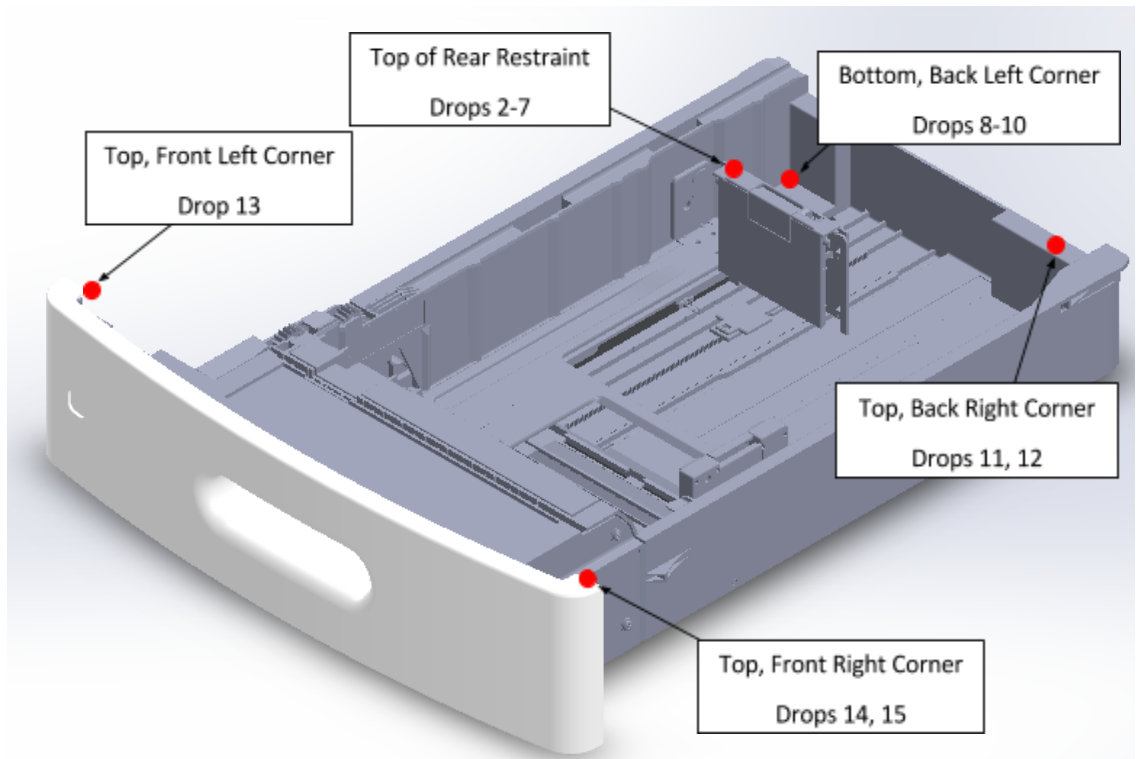


Figure 2. Accelerometer Locations for the Drop Tests

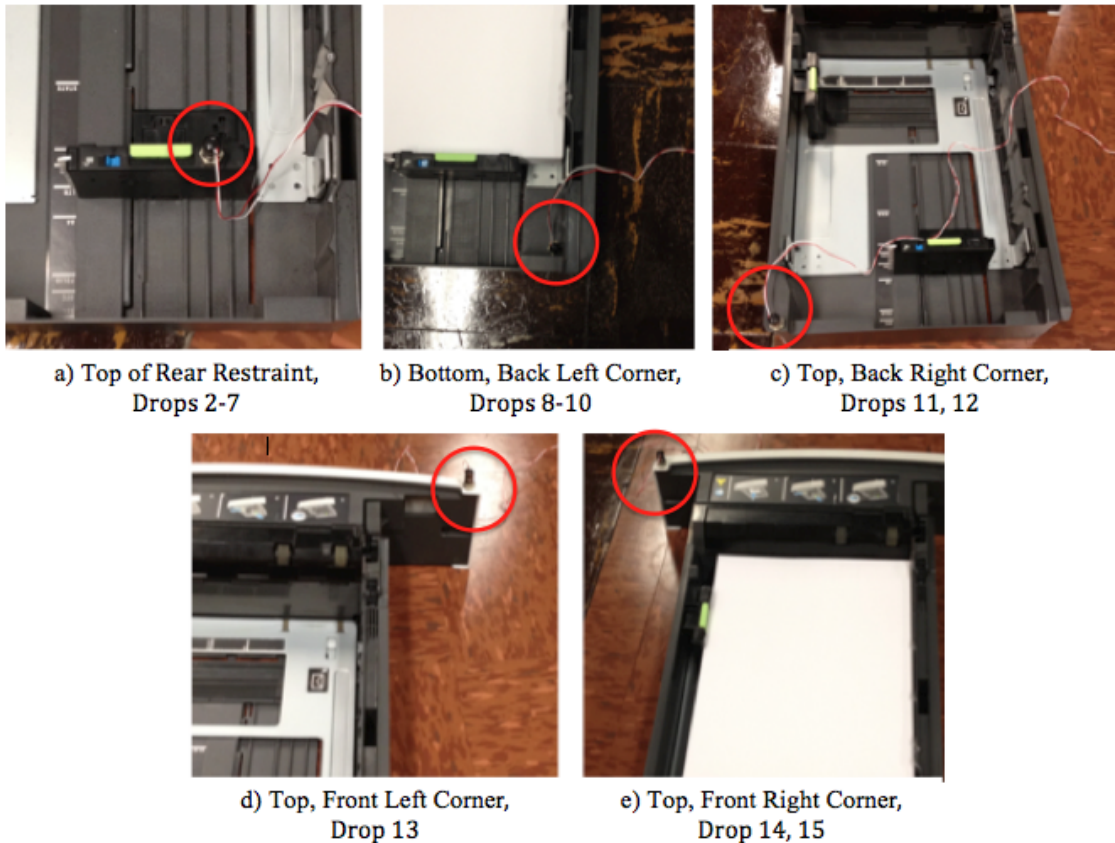


Figure 3. Accelerometer Locations for the Drop Test During the Test

The instantaneous acceleration the tray experiences as it hits the ground is important in predicting what areas of the tray will break and how they will break. The area of the tray that seemed to be experiencing the most acceleration was the front of the tray. It experienced an acceleration up to 3000 times that of the gravitational acceleration.

For the first three drops, the tray was dropped with no paper in it. From there, it had a full ream of paper in it, except for drops 10-14. The paper was included to account for a worst case scenario drop. Based on the results of the drops, the paper did not significantly increase in the acceleration, and in some cases the empty drop experienced higher accelerations. This is possibly due to the damping effect of paper on the tray.

The tray did not break until drop 7 when the friction wheel assembly burst out of the tray due to fracture in the pin. The friction wheel assembly is the part that causes friction on the collected paper so only one piece is selected and remaining pieces are left in the tray. This piece can be seen in Figure 4 and is in the housing shown in Figure 1 (a). When this assembly broke, it was an unexpected failure, so we added this to our list of failure modes. In this drop test, the accelerometer was placed on the rear restraint of the tray (Figure 3 (a)) and it experienced an acceleration 546 times greater than the gravitational acceleration (Figure 5).



Figure 4. Friction Wheel Assembly

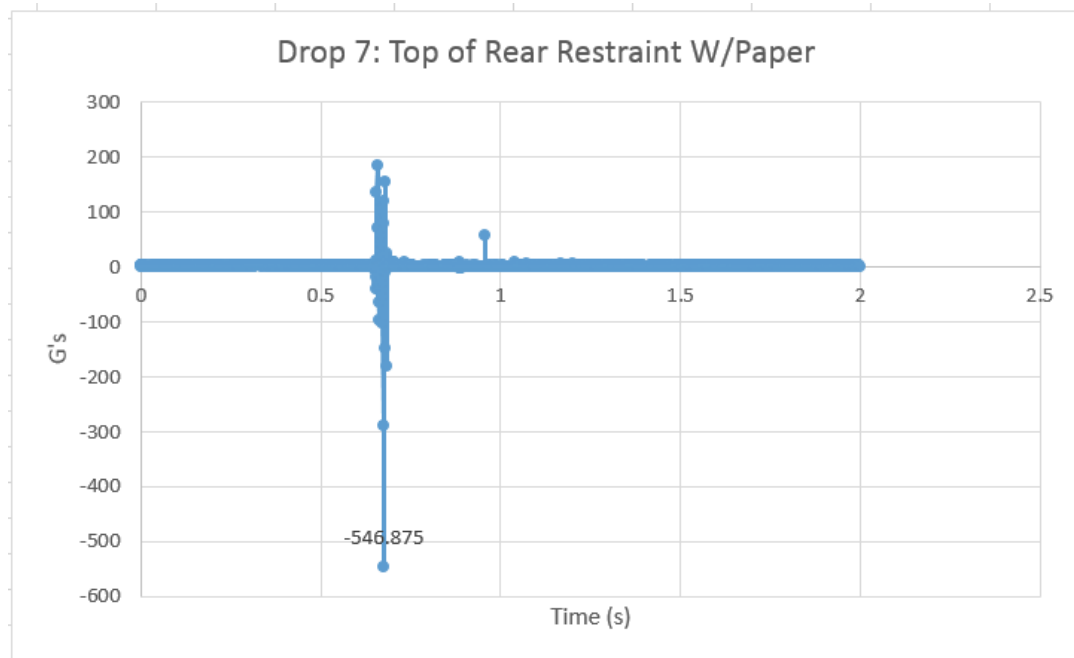


Figure 5. Drop 7 – Top of Rear Restraint with a Ream of Paper

On drop 8, the accelerometer was placed on the bottom of the back left corner of the tray (Figure 3 (b)). During this test, the attachment points of the front plate broke and

the plate became loose on the left side. The screw which holds the front plate in place also broke from its casing. One of the locator pegs found on the inside of the front plate broke off during this drop as well. These failure locations were unexpected and were then noted for future reinforcement. Figure 6 shows these failures and their locations. This location experienced an acceleration 390 times greater than the gravitational acceleration during this test (Figure 7).

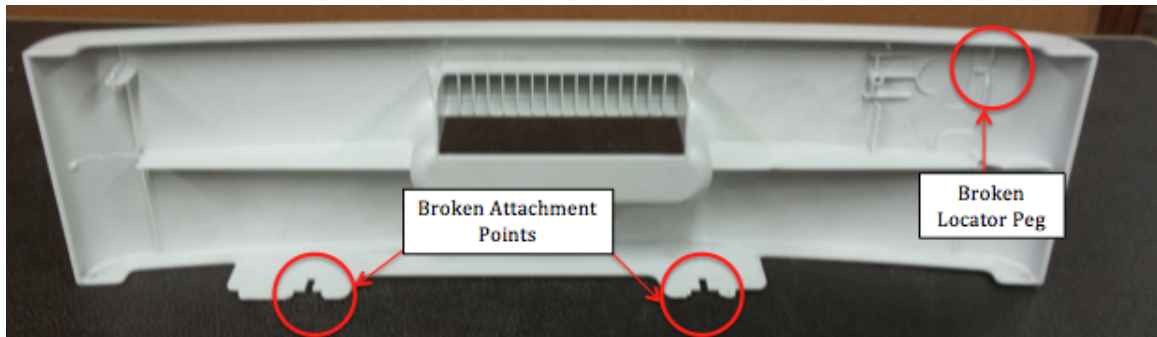


Figure 6. Front Plate Failures after Drop 8

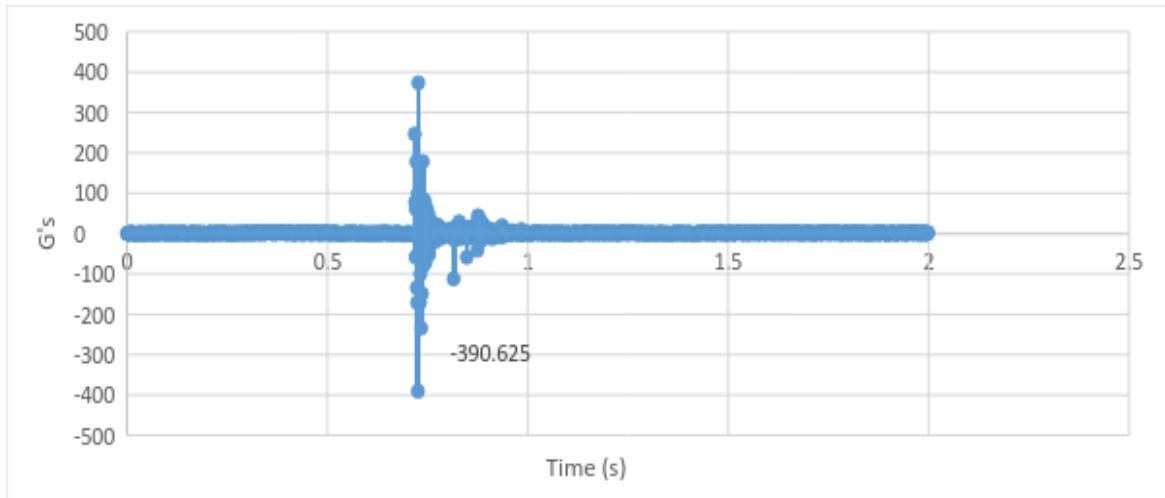


Figure 7. Drop 8 – Bottom, Back Left Corner of Tray with a Ream of Paper

The tray experienced no more breaks until drop 15 when the paper size sensors (Figure 1 (b)) completely failed. The paper size sensors failed because they became free to move and would no longer lock into a position to indicate a certain paper size. This

was an unexpected failure and was noted for future design changes. The accelerometer for this drop was placed on the top of the front right corner of the tray (Figure 3 (e)). The tray experienced a maximum acceleration of 3,085 times greater than the gravitational acceleration. This was the highest recorded acceleration (Figure 8). The second highest acceleration being 2,134 times that of gravitational acceleration at the same location. This location experienced extremely high accelerations which explains the earlier breakage of the front plate.

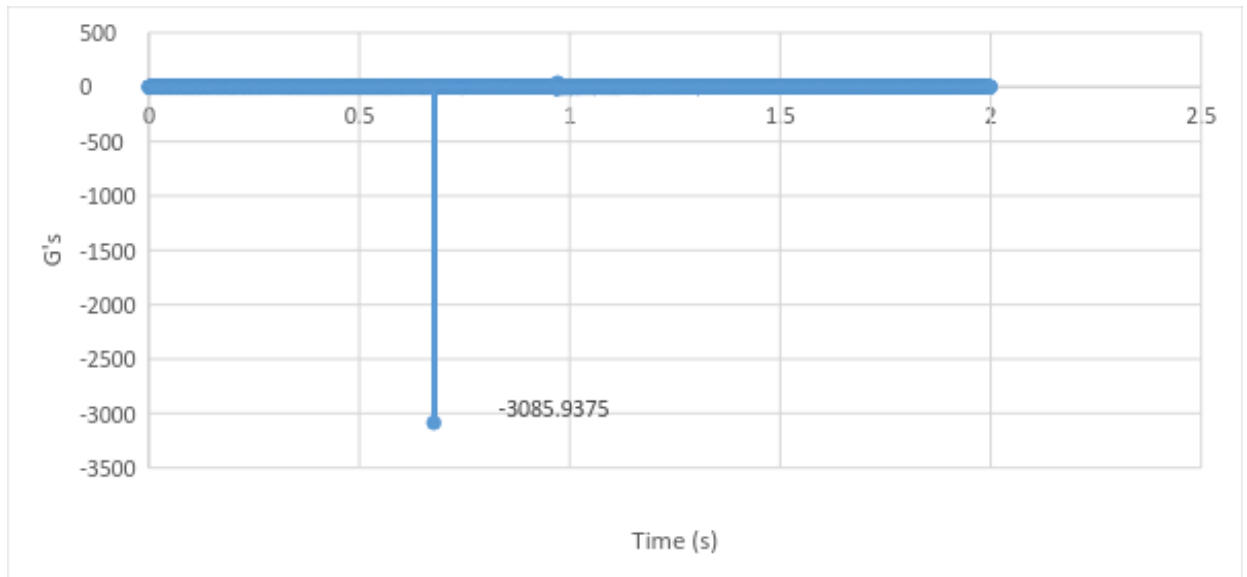


Figure 8. Drop 15 – Top, Front Right Corner with a Ream of Paper

From this point, the tray was dropped unrecorded in order to observe what else would break. By drop 22, the front of the tray had completely separated itself from the tray. This major failure agreed with our assumptions and was included in our reinforcement designs. From these drops, it was recorded that the front of the tray absorbs a lot of the force when the tray collides with the ground. Each spot that broke during the tests was recorded for possible reinforcements.

ii) Slam Test Experiment

Introduction

Various failure modes are detected when the user shuts the tray in an aggressive or forceful manner. We are relating to this gesture by calling it a paper tray slam. During a paper tray slam there are peak stresses that occur in certain areas of the paper tray causing failures of both ductile and brittle fractures. These failures will occur during a paper tray slam(s) when (A) the local stresses occurring are larger than the yield strength and (B) when the fatigue strength reaches its limit over a cyclic loading.

Failure “A” above occurs when the yield point of a material is reached. This point is defined as the stress at which the material begins to deform plastically. When the stress (σ), at any time, being experienced by the material in the paper tray becomes greater than the yield stress of the material (S_{ys}) there is said to be a failure in the form of a ductile fracture. This is highlighted by equation 1.

$$\sigma \geq S_{ys} \quad \text{Equation 1}$$

We are tasked with providing the tray with a fatigue life of 150 cycles of high impact paper tray slams. To accomplish this task the fatigue strength needs to be increased in the areas where the endurance limit of the material is breached. This is shown in equation 2, where S_{N-150} is the fatigue strength of the material at 150 cycles (N) and σ_{max} is the maximum stress acting on the material.

$$\sigma_{max} \geq S_{N-150} \quad \text{Equation 2}$$

Test Procedure

To test and analyze the stresses occurring in the tray during a paper tray slam, we used an accelerometer placed in various locations throughout the tray. There were five locations on the tray that were chosen through both failure modes reported by customers and by potential failure modes that we predicted as a team. The locations are shown in Figure 9 and consisted of three locations on the front of the tray, one location on the rear paper restraint, and one location on the rear wall of the tray.

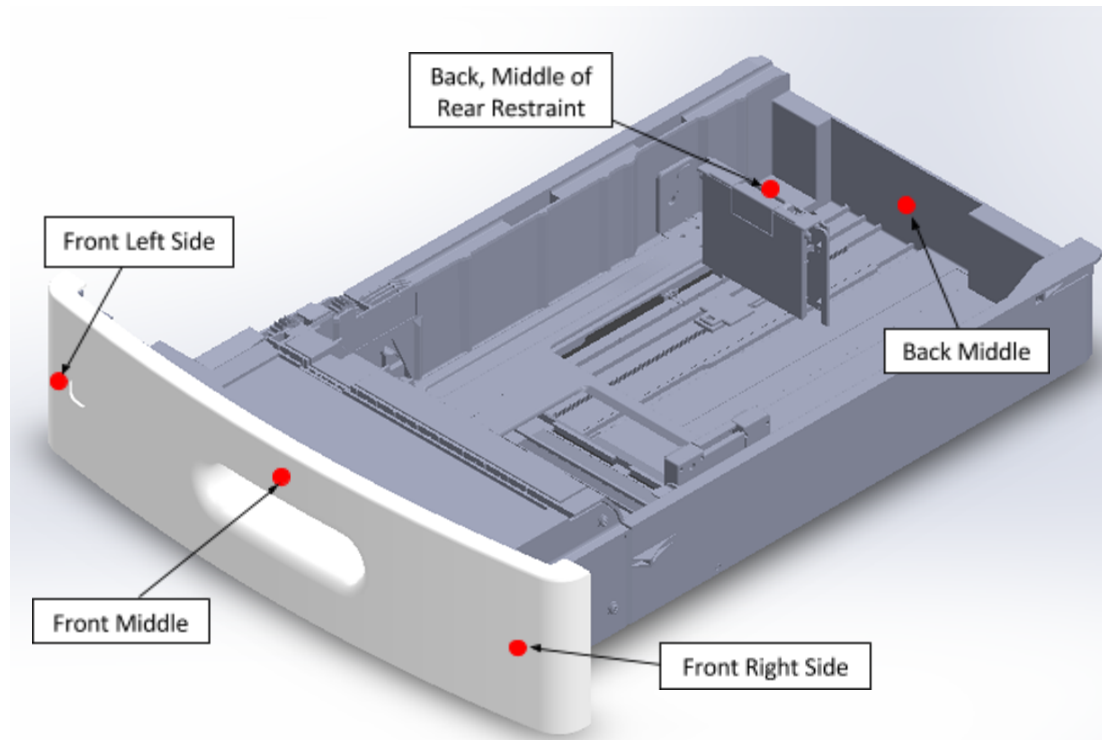


Figure 9. Accelerometer Locations for the Paper Tray Slam Test

An accelerometer was connected to a computer which gathered our readings. When the paper tray was slammed shut, samples were taken of the accelerations occurring at the accelerometer's locations every 0.001 seconds. This data was then plotted and used to find the peak acceleration at the accelerometer's location. The accelerations were then used to calculate the stress occurring on each element to which the accelerometer was attached.

Rear Paper Restraint

The rear paper restraint (Figure 1 (a)) experienced a maximum acceleration of 781 times the gravitational acceleration ($7662 \frac{m}{s^2}$) with the tray fully loaded with paper (Figure 10).

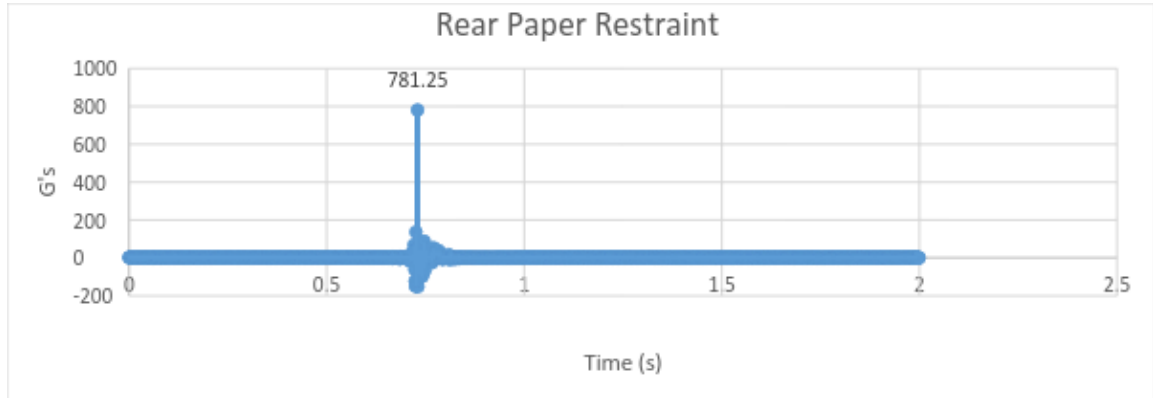


Figure 10. Slam Test – Acceleration of the Rear Restraint

To find the forces exerted on the rear paper restraint, we multiplied together the mass of the ream of paper and the maximum acceleration (equation 3).

$$F_{rear_restraint} = m * a_{MAX} = (1.8 \text{ kg})(7662 \frac{m}{s^2}) = 13791 \text{ N} \quad \text{Equation 3}$$

To approximate the strength of the rear paper restraint we used simple beam calculations on the support of the rear paper restraint.

This force was used to calculate the load experienced by the rear restraint. Using this force ($F_{rear_restraint}$) and the perpendicular distance (d), we were able to calculate the maximum moment that the support experiences during a paper tray slam with equation 4.

$$M_{max_experienced} = Fd = (13971N)(.035m) = 462.7 \text{ Nm} \quad \text{Equation 4}$$

To approximate the maximum allowed moment ($M_{max_allowed}$) in the support we used the flexural modulus ($\sigma_{flexural}$) in equation 5.

$$M_{max_allowed} = \frac{\sigma_{flexural} * I}{y} = \frac{(2000 MPa)(5.625 * 10^{-10} m^4)}{.001 m} = 1163.5 Nm \quad \text{Equation 5}$$

Since $M_{max_allowed}$ is much greater than $M_{max_experienced}$ the rear paper restraint will not experience fracturing or plastic deformation over a single paper tray slam.

To analyze the rear paper restraint under multiple “paper tray slams” we used failure of fatigue calculations. Shown in equations 6 and 7, we found the number of “slams” the rear restraint can withstand to be approximately 3670.

$$N_{current} = .5 * \exp\left(\frac{\ln\left(\frac{\sigma_{flexural}}{\sigma_{critical}}\right)}{b}\right) = 3673 \quad \text{Equation 6}$$

$$b = -\frac{1}{6.3} * \ln\left(\frac{2\sigma_{flexural}}{\sigma_{UTS}}\right) \quad \text{Equation 7}$$

Since 3670 paper tray slams is much greater than our desired system durability of 150 slams the rear paper restraint does not deform plastically under multiple “paper tray slams”.

It has been shown during testing and reported to us by Lexmark that the position of the rear paper restraint can be compromised during “paper tray slams”. This is caused by fatigue in the spring that clamps the restraint into a gear system. If this fails, then the tray cannot work because there is no longer anything to grip the paper in place. To overcome this failure mode we constructed a new design of the rear paper restraint for the “Letter” and “A4”.

Friction Wheel Assembly

During our drop tests, we saw that the rigidity of the friction wheel assembly (media operator) was an issue. This part resides in a plastic housing at the top of the

elevator tray, where the paper is taken up (Figure 1 (b)). The shaft of the device was the first fracture that the part experienced when it broke on the seventh drop. Since there was no way to have the accelerometer directly on the shaft of the device we were unable to directly calculate the acting forces. However, we were able to approximate the moment required to fracture the shaft using a simple beam approximation (Figure 11).

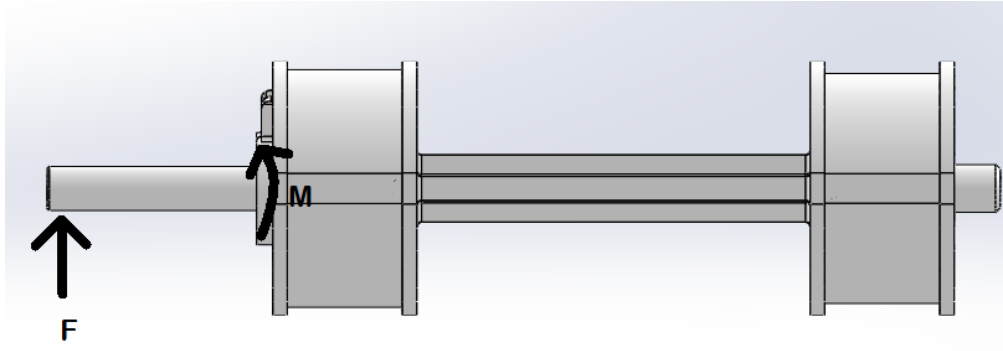


Figure 11. Free Body Diagram of the Friction Wheel Assembly

Using the Flexural Modulus ($\sigma_{flexural}$) of ABS plastic, the moment of inertia (I), and the axial distance (y), we calculated a maximum allowable moment of 19.8 Nm on the shaft, shown in equation 8.

$$M_{max_allowed} = \frac{\sigma_{flexural} * I}{y} = \frac{(2000 \text{ MPa})(2.198 * 10^{-11} \text{ m}^4)}{.0023 \text{ m}} = 19.8 \text{ Nm} \quad \text{Equation 8}$$

Since we knew that the rigidity of the shaft was an issue, we began designing a new shaft assembly for the friction wheels.

B) Analytical Testing

Introduction

Testing must be conducted in order to identify additional failure points of the paper tray that should be reinforced or redesigned. Results from analytical testing is important to understand the parameters that define the design, such as: strength, proper function, and aesthetics. As defined in the definition of success, the new design for the

“Industrial Paper Tray” must withstand the force of an individual sitting on a fully opened paper tray and begin to lift the opposite end of the printer off the table top. The new paper tray design must also withstand a force from the side of the paper tray and start to twist the printer when it is fully extended. Analyzes were conducted on the paper tray for each of these tests to determine any failure points.

The tests were simulated using Finite Element Analysis (FEA) on the Solidworks model. Solidworks has a tool called SimulationXpress Analysis Wizard, which allows you to analyze the stress experienced in the model by applying forces, creating fixtures, and defining the tray material. Given those inputs, the SimulationXpress tool outputs the displacement and von Mises stress experienced by the part during testing.

i) Sitting Test Procedure

For the simulation of an individual sitting on the paper tray, the paper tray was broken down to just the back corner of the paper tray where the printer’s support wheels make contact with the paper tray rails. A force gauge was attached to the front edge of the full open paper tray and the force required to tip the printer forward was measured. A free body diagram (FBD) of the paper tray was created in order to determine the applied load from the printer’s support wheels on the tray rails. Figure 12 shows the simplified original part used for the stress analysis along with the location of the reaction force and fixture points.

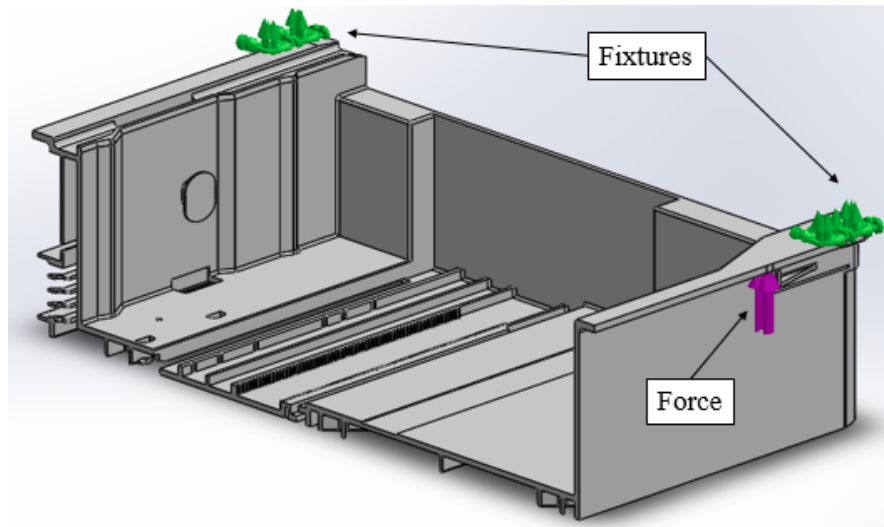


Figure 12. Sitting Test Reaction Force and Fixture Locations

The reaction force, represented by the purple arrows, are in the same location on both side of the paper tray. The fixture points, represented by the green arrows, are the points where the printer supports the tray rails when the tray is pushed down.

Test Results

The weight of the heaviest printer model is used to calculate the force needed to tip over the printer, which equals 65 lbs. The heavier printer results in the largest force applied to the paper tray to tip it forward. Figure 13 is the free body diagram used to calculate the force (P) needed to tip the printer over when an object rests on the front edge of the paper tray.

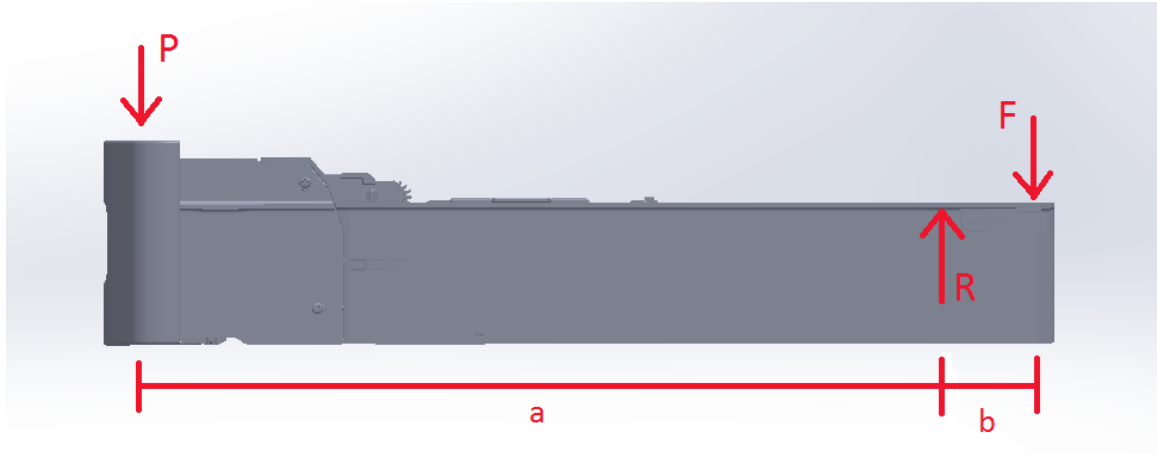


Figure 13. Sitting Test Free Body Diagram

The applied load (P) needed to tip over the printer was determined to be 18.5 pounds (lbs). The applied load was determined using a force gauge attached to the front edge of the paper tray. The force measurement was recorded just before the printer started to tip forward. The reaction force (R) on the paper tray rails was calculated using a moment summation about the support force (F). Equation 9 shows the formula used to calculate the reaction force. The dimensions from the free body diagram are $a = 17.45$ in. and $b = 1.378$ in.

$$P(a + b) - R(b) = 0 \quad \text{Equation 9}$$

The reaction force on the tray rails at the printer's support wheels is equal to 253 lbs. The reaction force applied to each tray rail used for the FEA in Solidworks is the reaction force divided by two, which is 126.5 lbs. After simulating the forces on the paper tray using the SimulationXpress Analysis Wizard tool, the resulting maximum stress experienced by the tray rail is 346 MPa, however the yield strength of ABS at room temperature is 68.8 MPa. Based on the results, the tray rails will fail and break when an individual sits on the edge of a fully open paper tray and causes the printer to tip forward. The paper tray rails may start to plastically deform under initial conditions, and they will fail after repeated loading or if the load is applied abruptly.

ii) Side Load Test Procedure

The new paper tray design must also withstand a force from the side of the paper tray when it is fully extended. The side load test simulates an object or individual pushing the fully open paper tray from either side. The printer starting to twist or move would indicate for the individual to stop pushing the printer. The side load test causes a reaction force to occur at the rear of the paper tray where the tray rail hits the printer. The FEA for the side load test is similar to the sitting test except the force is applied from the side, and the force applied should be large enough to move the printer. Also like the sitting test, only the rear section of the paper tray is analyzed since that is where the reaction force and fixture occur. The printer was positioned on a wooden table top and a force gauge was attached to the front of the fully open paper tray. The force gauge was pulled normal to the side of the printer, and just before the printer started to move or twist the force measurement was recorded. Figure 14 shows the force location and fixture reaction on the paper tray when conducting the side load test.

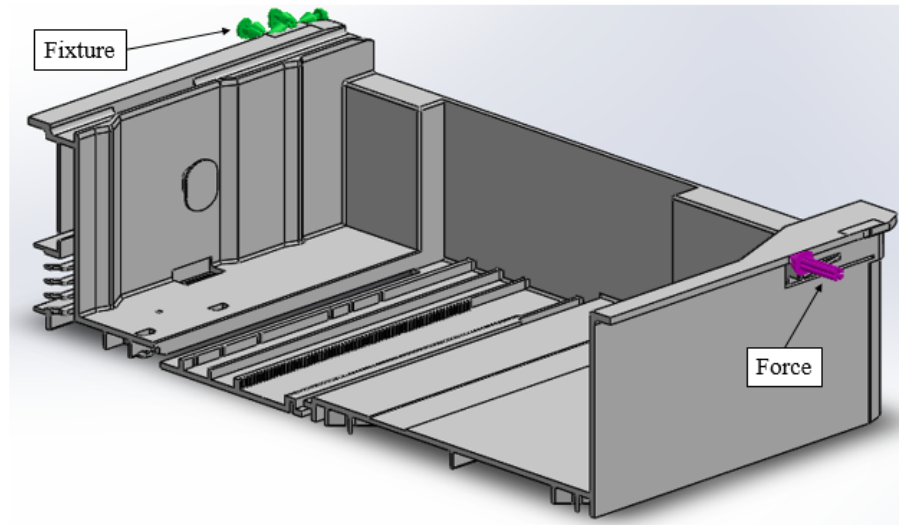


Figure 14. Side Load Reaction Force and Fixture Location

The reaction force, represented by purple arrows, is perpendicular to the side of the tray rail. The fixture point, represented by green arrows, is the location where the

printer supports the tray from the opposite side of the applied force. A FBD was created to calculate the reaction force experienced by the tray rail when it touches the printer.

Test Results

The side load test was conducted to simulate a fully-opened paper tray being pushed from the side. A force gauge was attached to the front corner of the fully-opened paper tray and pulled in the normal direction from the tray's side. The force measurement on the gauge was recorded just before the printer started to move. Figure 15 is the free body diagram of the paper tray used to calculate the reaction force (R) on the tray rail.

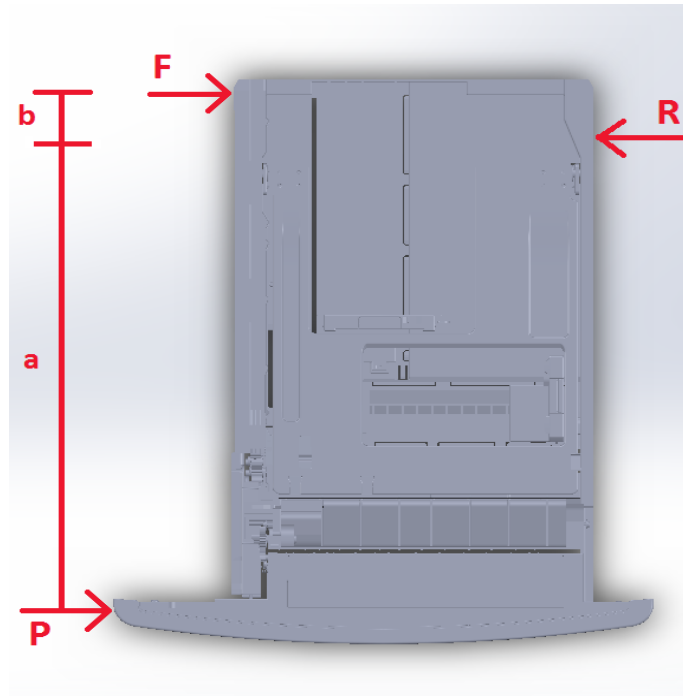


Figure 15. Top View Free Body Diagram

The applied load (P) needed to twist the printer was determined to be 15.3 lbs. The reaction force (R) on the paper tray rails was calculated using a moment summation about the support force (F). Equation 10 shows the formula used to calculate the reaction force. The dimensions from the free body diagram are $a = 17.45$ in. and $b = 1.378$ in.

$$P(a+b) - R(b) = 0 \quad \text{Equation 10}$$

The reaction force on the tray rails at the printer's support wheels is equal to 209 lbs, so this is the force applied to the tray rail for the FEA in Solidworks. After simulating the forces on the paper tray using the SimulationXpress Analysis Wizard tool, the resulting maximum stress experienced by the tray rail is 500 MPa. This stress measurement is much larger than the yield strength of ABS, so the tray rail will crack and deform under the conditions of the side load test. Also, the clip, located on the back corner under the rail that prevents the tray from sliding completely out, may break if the applied force is abrupt.

iii) Side Paper Restraint

The rigidity of the side paper restraint was tested through the use of a slender beam approximation. The side paper restraint impedes the moment in the linear direction (shown in Figure 16) through the use of two vertical pieces molded into the plastic. These two pieces of plastic were then approximated as slender beams in order to find the maximum allowed moment ($M_{max_allowed}$) and by using the flexural modulus ($\sigma_{flexural}$) in equation 11. The equation is multiplied by two since there are two slender beams being analyzed.

$$M_{max_allowed} = 2\left(\frac{\sigma_{flexural} * I}{y}\right) = 2\left[\frac{(2000 \text{ MPa})(4.982 * 10^{-11} \text{ m}^4)}{.0045 \text{ m}}\right] = 44.4 \text{ Nm} \quad \text{Equation 11}$$

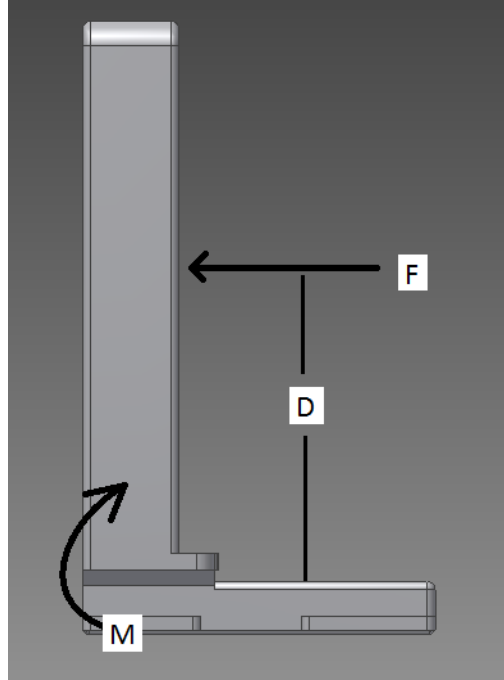


Figure 16. Moment and Force Diagram of Side Restraint

The $M_{max_allowed}$ was then manipulated to find the maximum allowable force (F_{max}) acting on the side restraint (Equation 12).

$$F_{max} = M_{max_allowed} / D = 44.4Nm / 0.1m = 444 \text{ N} \quad \text{Equation 12}$$

V. New Design

A) Friction Wheel Assembly

The design for the new friction wheel assembly consists of three separate parts: (1) the shaft and (2 & 3) the two friction wheels (Figure 17). The shaft was designed out of cold rolled 1020 steel and manufactured from a stock 8 mm diameter shaft. The shaft will be machine lathed down on each end to fit in the slots of the housing for the friction wheel assembly. It was also lathed to form two D shaped slots to hold and drive the friction wheels. Also, on the driving end of the shaft, it was tapped to allow the driving gear to be fastened. This driving end of the shaft is fastened to the existing drive gear with a M2 machined screw.

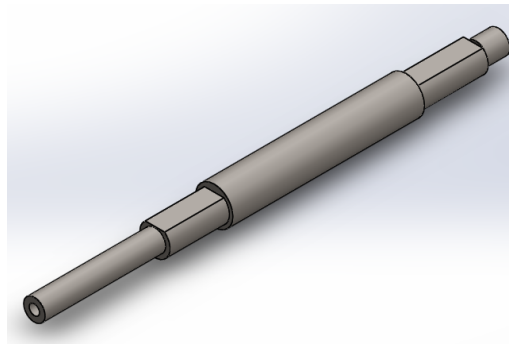


Figure 17. Steel Shaft for New Friction Wheel Assembly

The friction wheels are two separate wheels resembling a similar shape and size as the current assembly (Figure 18). For the prototype the wheels were 3D printed out of ABS plastic. The wheels are able to slide directly on to each end of the shaft. The wheel on the driving end of the shaft is fastened by the driving gear and the wheel on the other end of the shaft is secured by the housing of the friction wheel assembly.

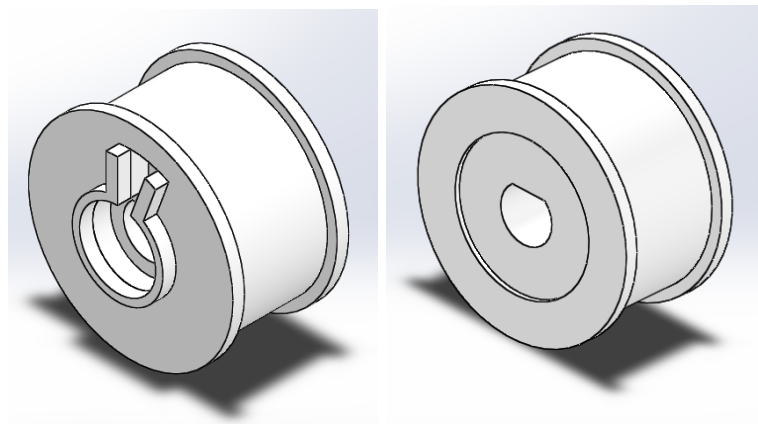


Figure 18. Driving Friction Wheel (left) and Non-Driving Friction Wheel (right)

The resulting design of the new friction wheel assembly is shown below in Figure 19. The two rubber media separator “tires” were added to each of the wheels. These tires are the same parts used in the current friction wheel assembly.

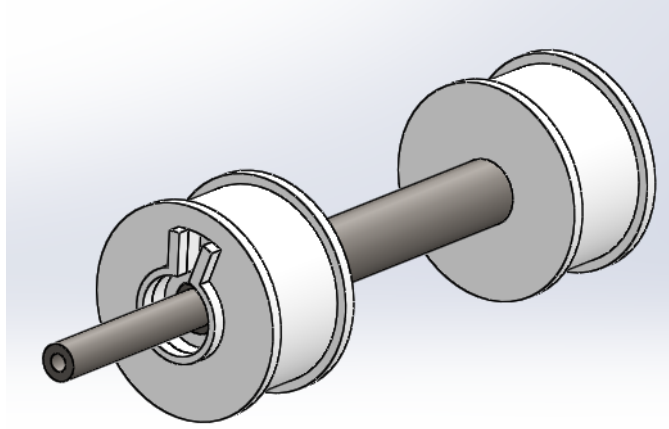


Figure 19. New Design for Friction Wheel Assembly

To analyze the new design's rigidity we calculated the new shaft's maximum allowed moment using a simple beam approximation as shown in equation 13.

$$M_{max_allowed} = \frac{\sigma_{flexural} * I}{y} = \frac{(200000 \text{ MPa})(2.198 * 10^{-11} \text{ m}^4)}{.0023 \text{ m}} = 1911.3 \text{ Nm} \quad \text{Equation 13}$$

This maximum moment of 1911.3 Nm for the new shaft is much greater than the maximum moment of 19.8 Nm for the currently used shaft. This results in a friction wheel assembly of great rigidity.

B) Metal Tray Body

The paper tray rail was previously identified as a failure part that needed to be redesigned and was confirmed by the finite element analyses conducted on the paper tray. There is not any room within the printer's housing to add supports or widen the tray rails, so the material must be changed to be capable of withstanding the required stress. 1020 cold-rolled steel is the material chosen since it easy to form during the manufacturing process and is already used for other parts in the paper tray assembly. The thickness of the steel is reduced to a common dimension of 1.4 mm in order to easily find sheet metal to manufacture. The same stress analysis using the forces from the previous test was

conducted using the new material and dimensions. The reaction force is applied to both rails equally and is 126.5 lbs each, and the yield strength of the 1020 cold-rolled steel is 350 MPa. The maximum stresses experienced by the tray during the sitting test and side load test are approximately 400 MPa and 298 MPa, respectively. Based on the results from the two analytical tests, the back corners of the tray rail will slightly bend approximately 1 to 2 mm. The bending won't result in failure and the paper tray will still be functional, and the rail can easily be positioned back to the correct position. The metal clip that prevents the tray from sliding completely out of the printer should be removed. During both tests there were high stress points underneath the tray rail where the metal clip cut-out is. The current design could be replaced with a plastic clip that is screwed into position and only needs a small cut-out, which would allow for more support of the tray rail.

The new paper tray design was changed to metal in order to add strength to the tray and also to fit within the allowable dimensions of the printer body. The plastic body on the back of the paper tray is being completely replaced with steel. The tray rail was extended along the whole length of the paper tray to eliminate any possible failure points. However, the new design must keep all of the same original features while accommodating the new features such as the elevator plate pivot pins, rear restraint, paper size sensor, and roller stop. Each of these new features were created into separate parts and are discussed later. Figures 20 and 21 show where the newly designed features are located on the new tray body.

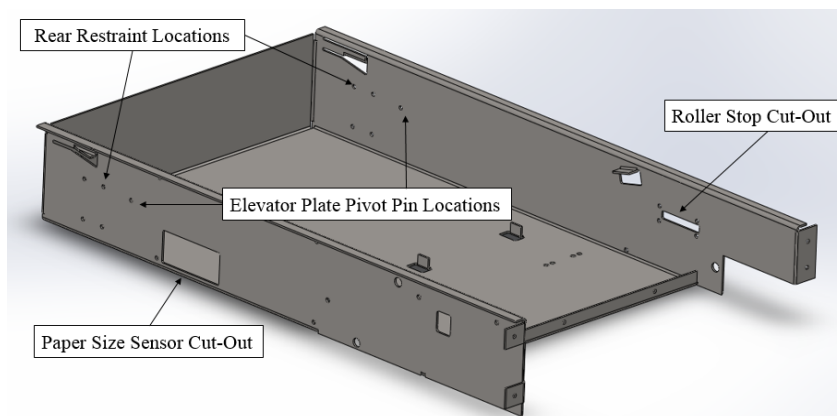


Figure 20. Left Side View of New Tray Body

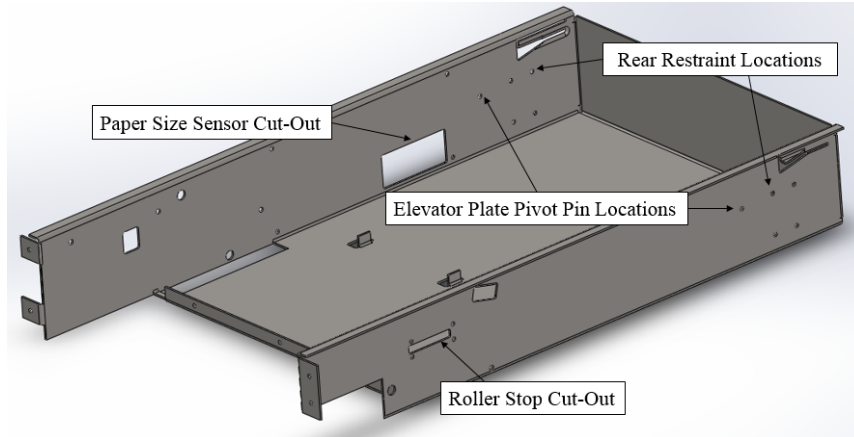


Figure 21. Right Side View of New Tray Body

The new steel wrapping design has two holes on each side of the body for the rear paper restraint to be attached to. The two holes are aligned vertically and the front set is for Letter size paper while the back set is for A4 size paper. The paper size sensor position has a rectangular cut-out on the left side of the tray, and the roller stop fits into a slot on the right wall of the tray. The paper size sensor and roller stop are both secured to the tray body using four M3.0x3 screws. The elevator plate pivot pins are located in the back of the tray just in front of the rear restraint, and they are secured to the tray by squeezing the metal around the hole and pinching the pin. Flaps were added to the front of the metal tray body to secure it to the front of the tray better and also to help absorb the impact when the paper tray is slammed abruptly.

C) Paper Sensors

The paper size sensor is mounted on the side of the paper tray (Figure 20) and pushes in tabs on the printer when the tray is completely inserted. The printer has four tabs on the left side of the housing and, depending on which one is pushed in, it determines the size of the paper inside of the tray. The paper size sensor tabs broke off the tray during the drop test, which showed that they needed to be redesigned to become more rigid. The new paper tray design was designed to be compatible with A4 and Letter sized paper. Figure 22 shows the paper size sensor for the A4 paper size.

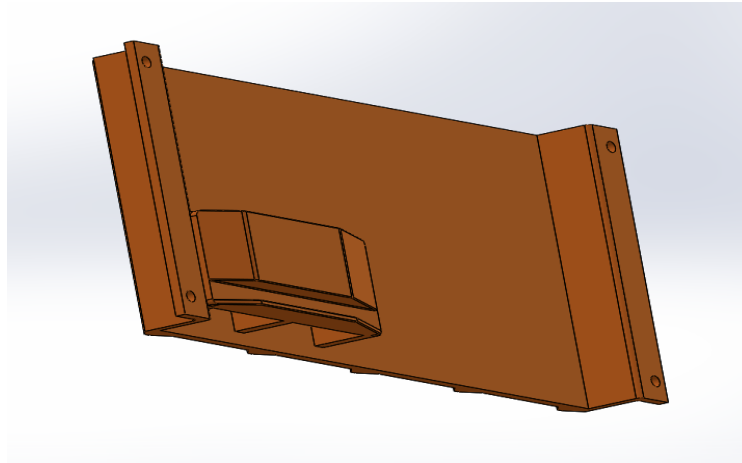


Figure 22. A4 Paper Size Sensor Front View

The front side of the part protrudes outside the tray wall and activates the tabs to signal what size paper is in the tray. Notice on the A4 sensor there is a slot missing on the bottom; this is the position required to signal to the printer the A4 paper size. The slot simply moves up to the next position to signal to the printer that there is Letter sized paper in the tray. This is a separate part that can will be bought by the user depending on if they plan to print Letter or A4. Figure 23 shows the back side of the paper size sensor, which is the paper alignment ribs. The paper alignment ribs are used to position the paper stack inside the tray to ensure the stack is square and even for optimal printing. The paper size sensor is secured to the tray body with four M3.0x3 screws located in each corner.

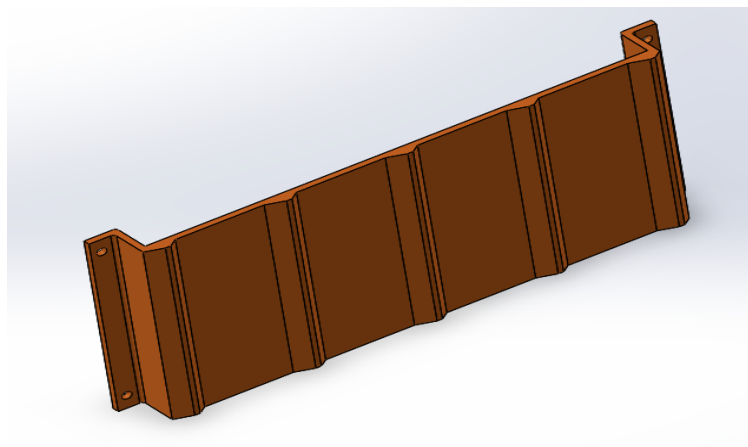


Figure 23. A4 Paper Size Sensor Back View

The paper size sensor part is made of ABS plastic and was manufactured using a 3D printer at the University of Tennessee facilities for the prototype. This part will be created using an injection mold for the new design.

D) Roller Stop

The roller stop is located on the right side of the tray body (Figure 20) and the feature ensures that the paper tray is fully inserted into the printer's housing. There is a small wheel located inside of the printer's housing that rolls over the roller stop, and once it has passed over the feature, the paper tray is fully closed. The tray body's new design is now made of sheet metal, so the roller stop feature needed to be replicated to function properly. Figure 24 shows the new part that is made from ABS plastic.

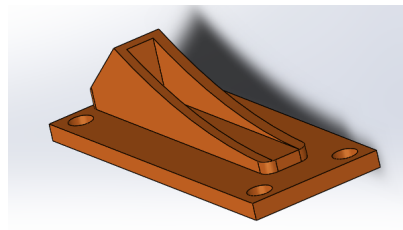


Figure 24. Roller Stop

The new part was designed to fit into a cut-out on the right side of the tray body, and it is secured using four M3.0x3 screws. The dimensions of the new design are identical to the original part, but a platform was added to the back side of the feature so it can be secured to the tray body. The prototype was created using a 3D printer at the University of Tennessee, but it is intended to be manufactured on a large scale using an injection mold.

E) Elevator Plate Pivot Pins

The elevator plate pivot pins are located on the side walls of the tray body, and their locations are shown in Figure 20. The pins attach the elevator plate to the tray body

and act as the pivot points for the plate. Like the roller stop, the elevator plate pivot pins cannot be duplicated using sheet metal. Therefore, the same dimensions were taken from the original design and used for a metal machined part. The new design now has a shaft centered on the back face of the pin that tightly fits inside a hole on the tray body's wall. The pivot pin is then secured onto the tray using a fine point hole punch and hammer. The 1020 cold-rolled steel sheet metal used to make the tray body is a relatively soft metal. Therefore, the metal directly adjacent to the pivot pin's hole can be struck with the hole punch and the metal will squeeze the pin securely inside the hole. Figure 25 shows the new design for the left and right elevator plate pivot pins

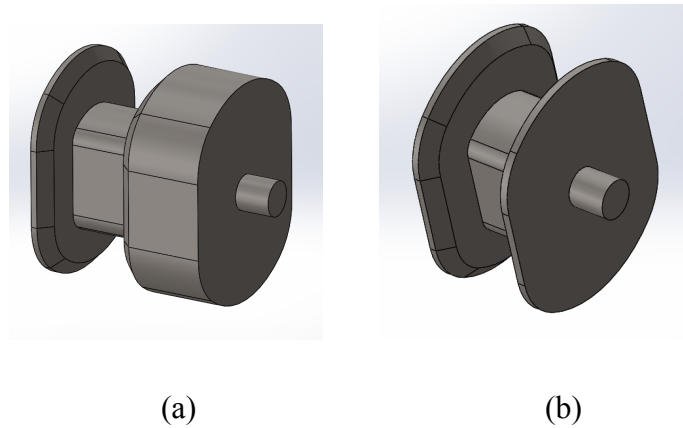


Figure 25. Elevator Plate Pivot Pins, (a) Left (b) Right

The elevator plate is not centered inside the paper tray so the pivot pin on the left side is slightly wider than the right pivot pin. This allows the elevator plate to support the paper stack so the paper can feed into the printer.

F) Rear Paper Restraint

The main function of the rear paper restraint is maintaining the correct position for the paper. When a paper tray slam occurs, the force of the paper onto the rear paper restraint can be as much as 13,791 N (found from maximum slam test). Over time, this causes wear on the gear teeth holding the restraint in its position. Also, a single slam can cause the restraint to move, therefore losing its function of holding the paper in place. To

overcome these failure modes, we redesigned the rear paper restraint (Figure 26) to allow it to withstand an increased amount of abuse from the user over a longer time span and to withstand the force of a single paper tray slam. Because of the constraints of the project, the gear track on the tray was eliminated entirely and the rear restraint can be secured into either A4 or Letter positions.

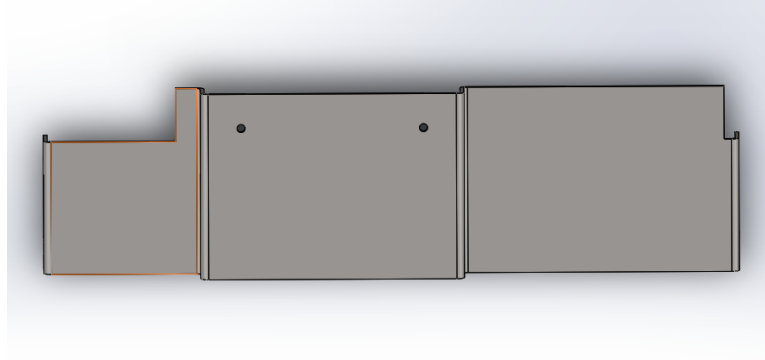


Figure 26. New Rear Restraint Design

The new restraint stretches from wall to wall of the tray and slides in from the top. The design allows for the elevator hinges to freely swing while not experiencing interference from the restraint. The face of the restraint remains in the center of the elevator tray where there is no material. To secure the restraint, the arms are screwed into the sides of the metal tray body (Figure 20). The new rear restraint is folded from 1.4 mm thick sheet metal. As seen in Figure 27, the original rear restraint is screwed securely onto the face of the newly designed rear restraint to make a part that has the rigidity of metal but the functionality of the original piece. Part of the old restraint was cut to remove excess plastic; this removed material has no function for this design.

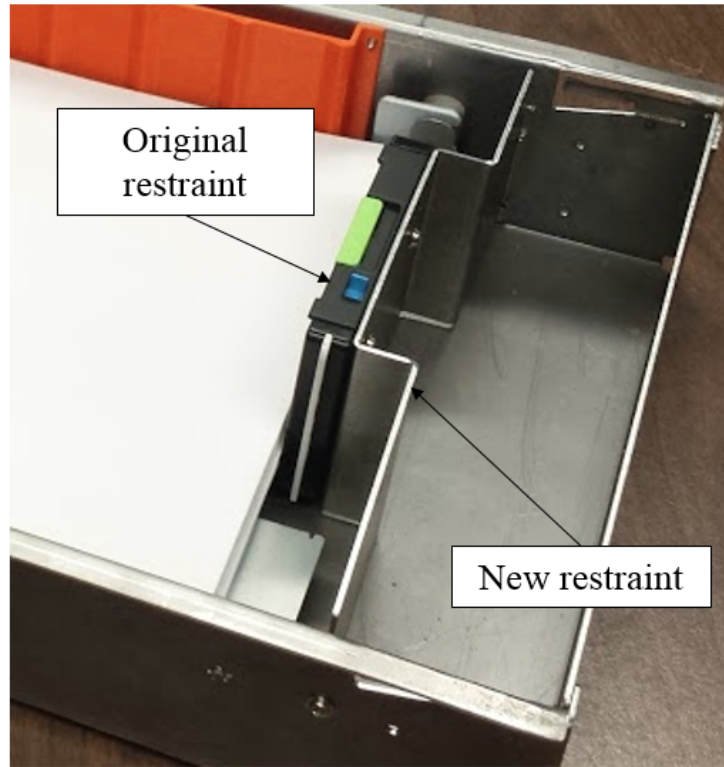


Figure 27. New Restraint with Old Rear Restraint Attached

The maximum stress that this new rear paper restraint will experience is 2.15 MPa as shown in equation 14. This is much less than the yield strength ($\sigma_y = 350 \text{ MPa}$) of the steel. Therefore, there will be no deflections on the restraint from a paper tray slam.

$$\sigma_{restraint} = \frac{F_{max}}{A} = \frac{13791 \text{ N}}{.006407 \text{ m}^2} = 2.15 \text{ MPa} \quad \text{Equation 14}$$

Using SimulationXpress Analysis Wizard, a force of 21 Newtons was applied across the face of the restraint. This force was derived from attempting to find the acceleration of the rear restraint just before its peak. An acceleration of about 19 m/s^2 was used. As seen in Figure 28, this gave a maximum deflection of 0.259 mm. With a yield strength of 350 MPa and a max stress of 42 MPa, the new rear restraint has a factor of safety of about 8, which can be observed from Figure 29.

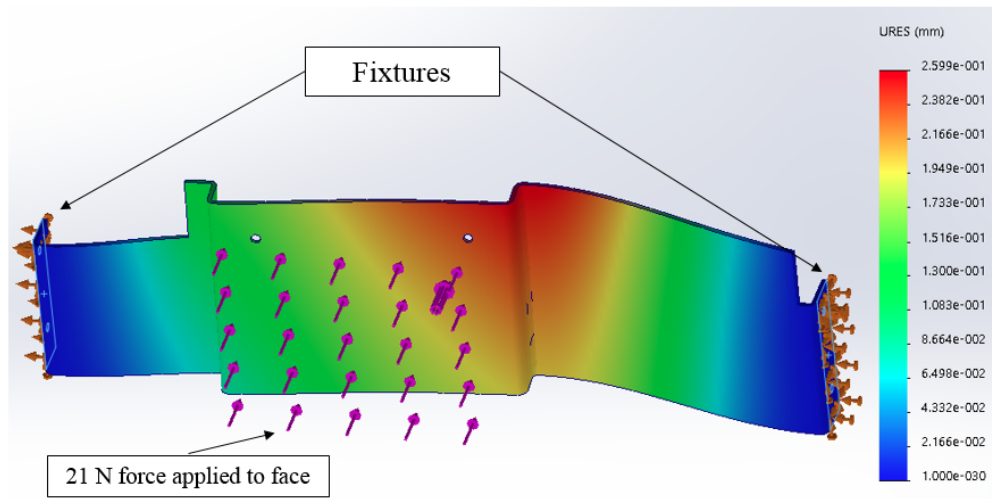


Figure 28. Displacement of Rear Paper Restraint (mm)

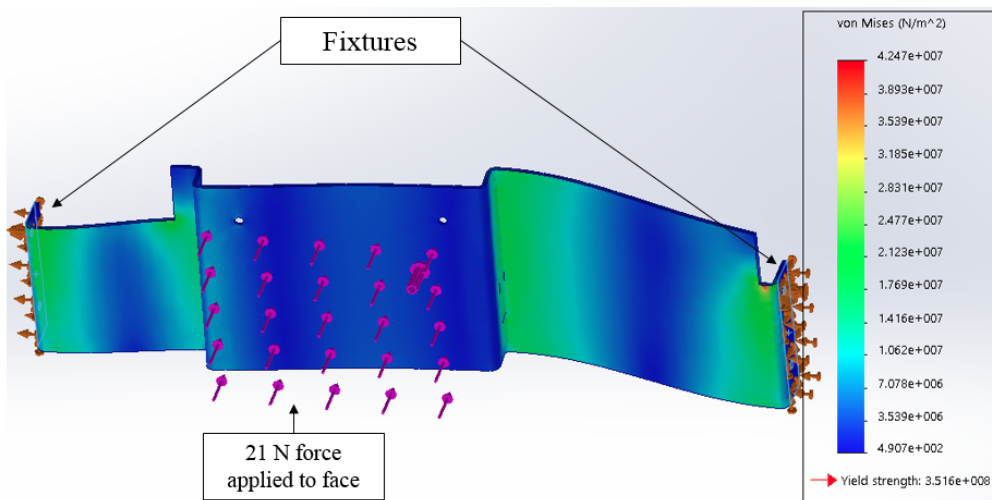


Figure 29. Stress of Rear Paper Restraint (Pa)

Since the only failure on the original rear restraint was due to the track in the tray, no new fatigue calculations were made. Screwing in the metal of the restraint should adequately hold the device in place while not hampering functionality. The maximum load of the rear restraint has increased from 1163.5 Nm to 56264 Nm based on equations 15 and 16. This added stability while keeping the functionality of the design, which will greatly improve the value of the part.

$$\sigma_{max\ allowed} = \sigma_{flexural} \frac{I}{y} = (2000\ MPa) \frac{5.625E-10}{.001} = 1163.5\ Nm \quad \text{Equation 15}$$

$$\sigma_{max\ allowed} = \sigma_{flexural} \frac{I}{y} = (2000\ MPa) \frac{(\frac{.0014 \cdot .06963^3}{12})}{.0014} = 56264\ Nm \quad \text{Equation 16}$$

To keep the tray from interfering with the insides of the printer, a section needed to be removed from the restraint. This change should not much alter the results of the Solidworks FEA or the maximum allowed load from equation 16. This alteration can be seen in figure 30 and is reflected in the design package.

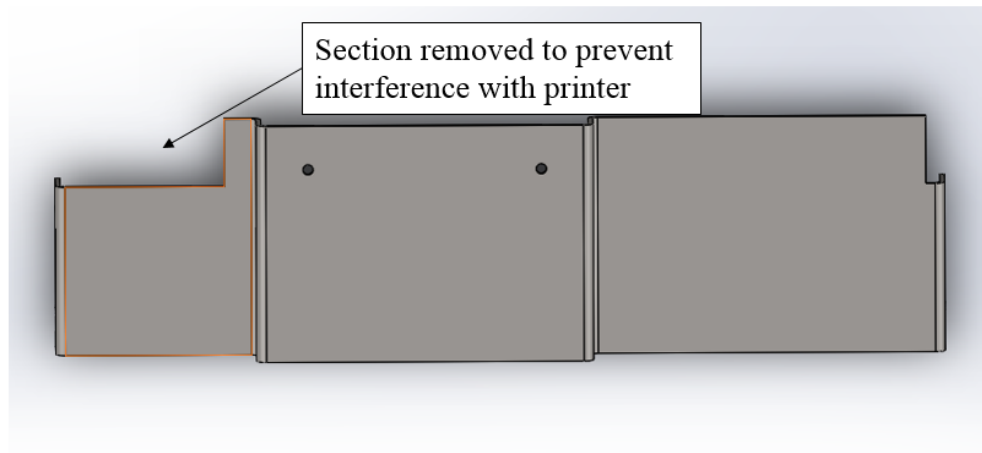


Figure 30. Altered Rear Restraint

G) Side Paper Restraint

Though there were no recorded signs or predicted potential failure of the original side paper restraint, a new design was still created due to design changes in the body of the paper tray. Specifically, the contact method and location were changed in our new design causing the old side restraint to no longer be adequate. The new design is using the existing housing for the side paper restraint and simply modifying its method of connection to the body of the tray. This is essentially done by adding 3 mm through holes to the bottom portion of the housing. These holes are then matched with the existing holes of the new steel tray and secured through the use of M3 bolts and M3 nuts.

The paper biases and springs from the original side paper restraint are used in the same manner as in the original design.

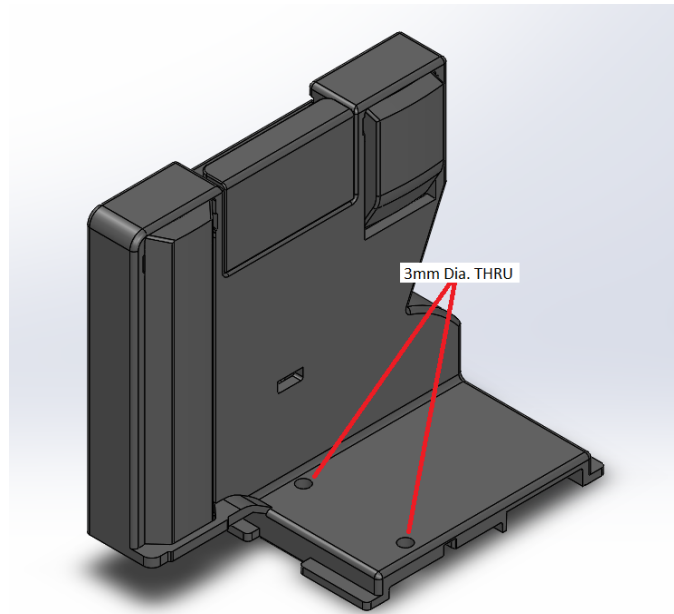


Figure 31: Rework Design of Side Paper Restraint

As already stated, there were no foreseen potential failures with the original but the rigidity of the side paper restraint was still analyzed. As stated in the testing section the maximum allowed force to act on the side restraint is 444 N. Since the original side restraint is used it is known that the rigidity will not change.

H) Front Face Plate

We redesigned the two front plate locator pegs (Figure 31) to increase their life expectancy. To redesign these locator pegs there were three options that we had to increase the critical forces: (1) change the material to one with a greater Young's Modulus, (2) decrease the length of the shock absorbers, or (3) increase the moment of inertia of the locator pegs. We decided against option one since it would not be able to

be executed easily and cost effectively. Option two was also not viable because the length is not able to be changed without compromising the locator pegs' main purpose. After this elimination, we were left with option three. We decided to change the locator pegs from a “plus” shaped figure to a cylindrically shaped figure to increase the moment of inertia. These cylindrically shaped locator pegs will replace the plus shaped ones and will be extruded from the mold of the front face plate.

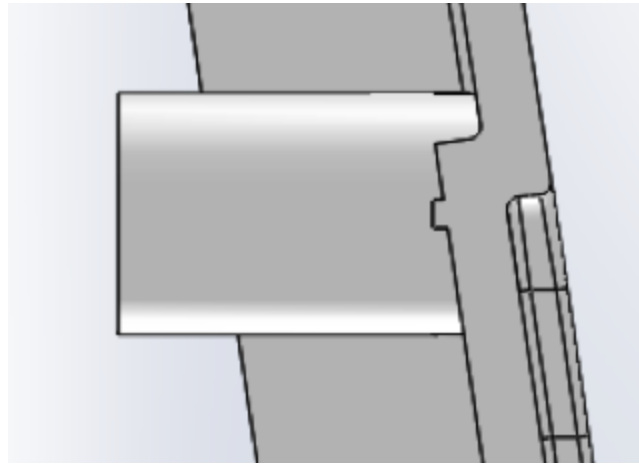


Figure 32. New Design of Location Pegs

We saw signs of failure to the front of the paper tray primarily during the drop test. During the drop test, the attachment points and the locator pegs were the main locations to fail. In the slam test, there were no physical failures. For these reasons, we choose to redesign the locator pegs and the attachment points of the front of the tray so it could stand up to this abuse.

We redesigned the locator pegs on the front of the paper tray by changing their shape. We changed the shape from a cross shape to a tube shape for the peg that would absorb the load from a drop. We did this because a tube shape would be able to absorb more force from a drop than the previous cross design.

We redesigned the attachment points between the two front pieces by removing their previous snap attachments and by replacing them with screws instead. Since the direct impact with the ground is what snapped these attachment points, we choose to add screws because this would provide a secure attachment between the pieces. The screws would allow less movement upon impact with the ground which would cause them to be less likely to break. Also, since the tray is much heavier in the back of the tray do to the metal, the body of the tray will take a predominant amount of the impact with the ground.

The front plate locator pegs also failed when the tray was dropped. Our new design had to withstand the force of impact so they would not shear off the part. We analyzed this impact by using a simple beam approximation (Figure 32).

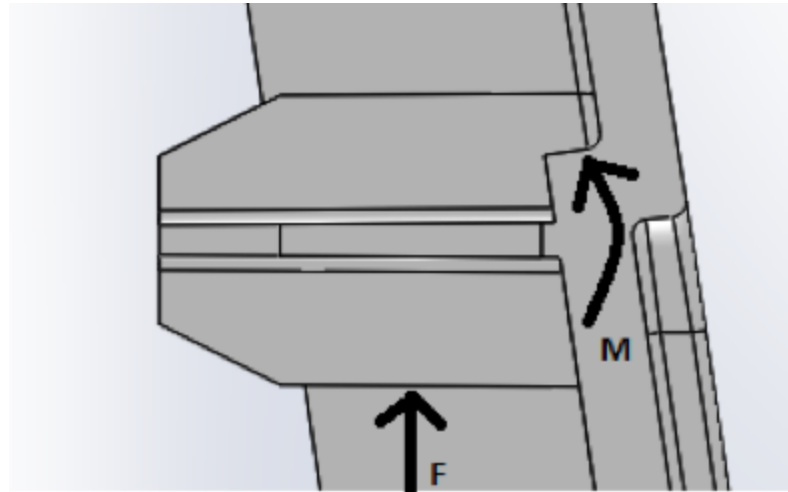


Figure 33. Force Diagram of Old Locator Peg

We determined the critical force ($F_{critical}$) and the critical moment ($M_{critical}$) from equations 15 and 16, where $a_{max} = 3086 * (9.81 \frac{m}{s^2}) = 30274 \frac{m}{s^2}$.

$$F_{max} = m_{casing} * a_{max} = (.22411 \text{ kg})(30274 \frac{m}{s^2}) = 6784.6 \text{ N} \quad \text{Equation 17}$$

$$M_{max} = F_{max} * r = (6784.6 \text{ N})(.0074 \text{ m}) = 50.21 \text{ Nm} \quad \text{Equation 18}$$

Again, we used the Flexural Modulus ($\sigma_{flexural}$) of ABS plastic, the moment of inertia (I), and the axial distance (y), to calculate the maximum moment without failure for the old design (equation 17) and the new design (equation 18).

$$M_{max\ allowed} = \frac{\sigma_{flexural} * I}{y} = \frac{(2000\ MPa)(8.435 * 10^{-11}\ m^4)}{.00493\ m} = 32.219\ Nm \quad \text{Equation 19}$$

$$M_{max\ allowed} = \frac{\sigma_{flexural} * I}{y} = \frac{(2000\ MPa)(2.883 * 10^{-10}\ m^4)}{.00493\ m} = 116.96\ Nm \quad \text{Equation 20}$$

The old design has a maximum allowable moment of 32.219 Nm which is below the critical moment of 50.21 Nm. This explains why the locator pegs failed in the drop test. Our new design has a maximum allowable moment of 116.96 Nm which is well above the critical moment. This means that one locator peg could take the full load of a drop. If the tray drops evenly on its base, it would share this load evenly between both of the locator pegs which would reduce the load and stress on each peg.

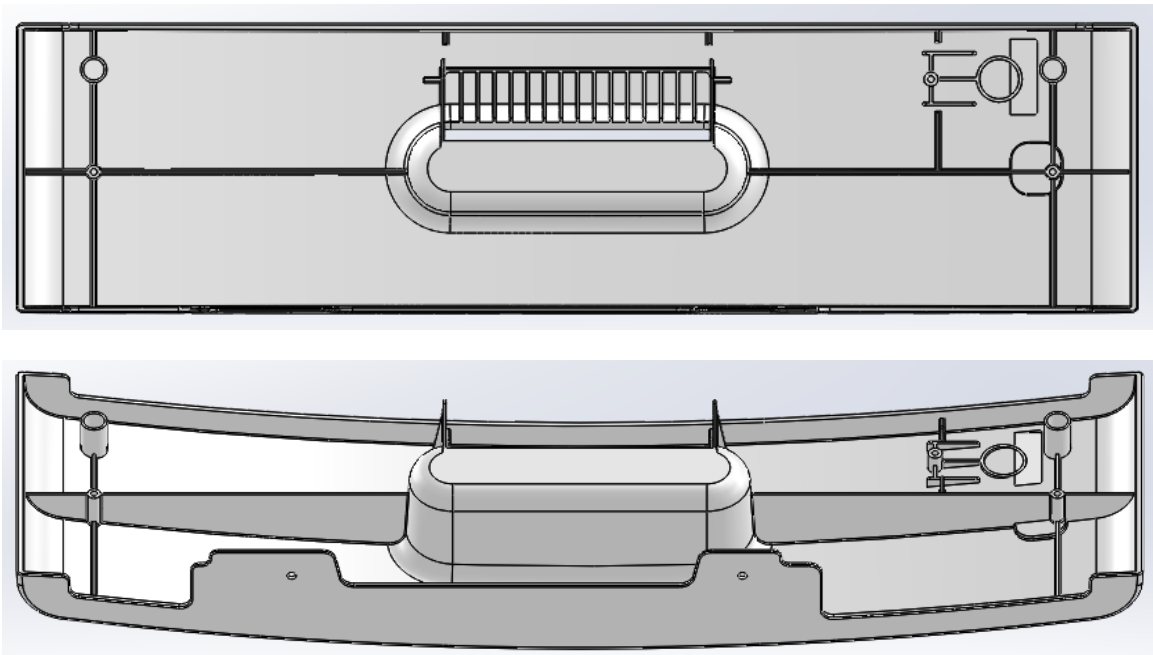


Figure 34. New Design of Face Plate. Back View (top) and Bottom View (bottom)

V. Cost Analysis

To analyze the cost of our newly designed paper tray we worked closely with Lexmark's rapid prototyping division. The cost analysis consists of the assumption that 100,000 units will be manufactured per year. The final cost analysis consists of a spreadsheet of all the changes with their corresponding cost of additions and cost of reductions. The cost of addition consists of the costs spent on material, labor, and manufacturing that it will take to add each part to the paper tray. The cost of reduction consists of the costs gained on material, labor, and manufacturing by removing parts from the current paper tray. To find the total cost of the new paper tray we subtracted the sum of the costs of reduction from the sum of the costs of addition.

VI. Manufacturing

The industrial paper tray will be used in specific industries where high abuse on the equipment is reported. This will be manufactured on a large scale for an estimated 100,000 units. Though the manufacturing of the paper tray will use commonly practiced processes, there will need to be an industrial design constructed in order to launch the industrial paper tray. The process will consist of common tooling and manufacturing processes such as injection molding, laser cutting, sheet steel forming, welding, steel milling, and assembly.

The new designs for the main body of the paper tray and rear restraint are being made with 1.4 mm thick, 1020 cold-rolled steel sheet metal. The sheet metal parts should be cut and stamped with a turret tooling machine and bent to form the design. When designing a new part using sheet metal multiple rules have to be considered so all of the important features can be duplicated. For instance, inside corners of cut-outs or punches have a radius of at least the thickness of the sheet metal. Also, the smallest cut-out or punch cannot be smaller than 1.5 times the thickness of the sheet metal. Any exposed corners of the sheet metal should be rounded to remove sharp edges and protect the users of the paper tray. When designing a 90-degree bend, the inner radius of the bend is equal to the thickness of the sheet metal and the outer radius of the bend is twice its thickness.

The new roller stop and paper size sensor parts are going to be manufactured using ABS plastic injection molds for large scale production. Based on the customers' request, the A4 or Letter paper size sensor can be installed into the paper tray during the final assembly. The elevator plate pivot pins are made from 1010 steel using a machining lathe. In order to make the manufacturing process easier for the pivot pins, new design should be adjusted so the curved edges consist of one continuous curvature and the fillets can be removed from all edges.

The new design for the friction wheel assembly will be formed from a stock 8 mm diameter shaft and two injection molded ABS plastic wheels. The shaft will be lathed down to the desired shape, including two D-grooves for the wheels to rest on and a M2X6 mm tapped hole on the drive end of the shaft. The two wheels will be injection molded with the same D-groove shape on the inside of the wheels that allow them to fit snugly on the shaft. The wheel on the drive end of the shaft is secured by the drive gear and fastened by an M2 machined bolt that is currently being used on the paper tray. The wheel on the opposite end is fastened by a C-clip that fits around the grooved shaft. Once all parts are manufactured, the friction wheel would then be assembled and placed in the industrial paper tray.

Manufacturing the side paper restraint consists of reworking the current assembly being used. This will consist of manufacturing the side paper restraint as currently being done. Once completed, this assembled part will be put through a rework process when two through holes of 3 mm diameter will be drilled into the base of the part. This part will then be fastened to the body of the tray through the use of two M3X6 mm machined bolts and two nuts.

The front faceplate of the new design will be redesigned and manufactured for all paper trays. This redesign consists of changing the shape of the locator pins from a plus shape to a circular shape. With this design change a new mold for the front faceplate will need to be manufactured. Once the mold is created, the new front faceplates will be manufactured in a similar manner through injection molding ABS plastic. These plates can then be used on all paper trays whether "industrial" or not.

VII. Summary

Overall, the new designs that we have created are more rigid and they can sustain higher loads. A summary of the loads that each designed part can sustain compared to its previous design is shown below in Table 1. The only design that did not increase was the side restraint. This part did become more rigid though because it is now screwed into place instead of being clipped into a gear system.

Table 1. Summary of Loads that Each Old and New Design Can Sustain

Part	Experienced	Old Design Allowable Result	New Design Allowable Result
Friction Wheel Assembly	n/a	19.8 Nm	1911.3 Nm
Rear Paper Restraint	462.7 Nm	1163.5 Nm	56264 Nm
Rear Paper Restraint	150 Slams	10.2 Slams	2530 Slams
Side Restraint	n/a	44.4 Nm	44.4 Nm
Front Face Plate Locator Pegs	50.21 Nm	32.219 Nm	116.96 Nm
Body of Tray - Side Load	298 MPa	68.8 MPa	350 MPa
Body of Tray - Sitting Test	400 MPa	68.8 MPa	350 MPa

VIII. Recommendations

For future drafts of this tray, we would make a few recommendations to provide greater ease in manufacturing and to create a stronger, lighter tray. First, we would

recommend making longer screw hole tabs on the rear restraint. This will make it much easy to drill holes in the rear restraint while it is being manufactured. Also, this will make the restraint stronger on the side because the tab will be less likely to bend or break.

We would also recommend using a thinner sheet metal for the body of the tray and adding weight-reducing cut outs. These changes will reduce the weight of the tray and make it more user friendly. Another revision that we would recommend would be using a harder steel. In addition to using a harder steel, making sure there aren't points in the tray that are susceptible to bending due to less material. Also removing the paper tray clip that prevents the tray from sliding out of the printer housing would reduce the stress and prevent the tray rail from bending.

The screws that secure the roller stop to the side of the tray body prevent the elevator plate from completely rotating. Therefore it is recommended that the holes in the roller stop are removed and replaced with pegs. The pegs would fit into the existing holes on the tray body and the roller stop could be secured in the same fashion as the elevator plate pivot pins. This would increase the clearance inside the tray body so the elevator plate would not be obstructed and the roller stop would fit more securely.

The designed metal shaft and plastic wheels for the friction wheel assembly need slight adjustments for ease of assembly. The metal shaft should be redesigned at the tip in order to directly rest on its pivot point. This will eliminate the extra plastic piece needed to secure the end of the shaft and thus creating a stronger connection. Also, the C-clip was unable to be used because it was hindering rotational movement by the shaft. For the prototype it was satisfactory to leave the C-clip off on the design since the wheel fit very snugly onto the shaft. For a more reliable system, the wheel would need to be redesigned in order to better fit the C-clip without hindering rotational movement.

In order to fasten many of the components to the tray many machined screws were used. This gave a secure fastening of the tray components, but due to the size and type of screws used there are many locations that hinder the movement of the tray when sliding it into position in the printer. In order to fix this issue, we suggest that low profile screws are used along with chamfer through holes are used. This will create a smoother

transition when sliding the tray into the printer and will also give a sleeker look to the paper tray.

Appendix A - Gantt Chart

