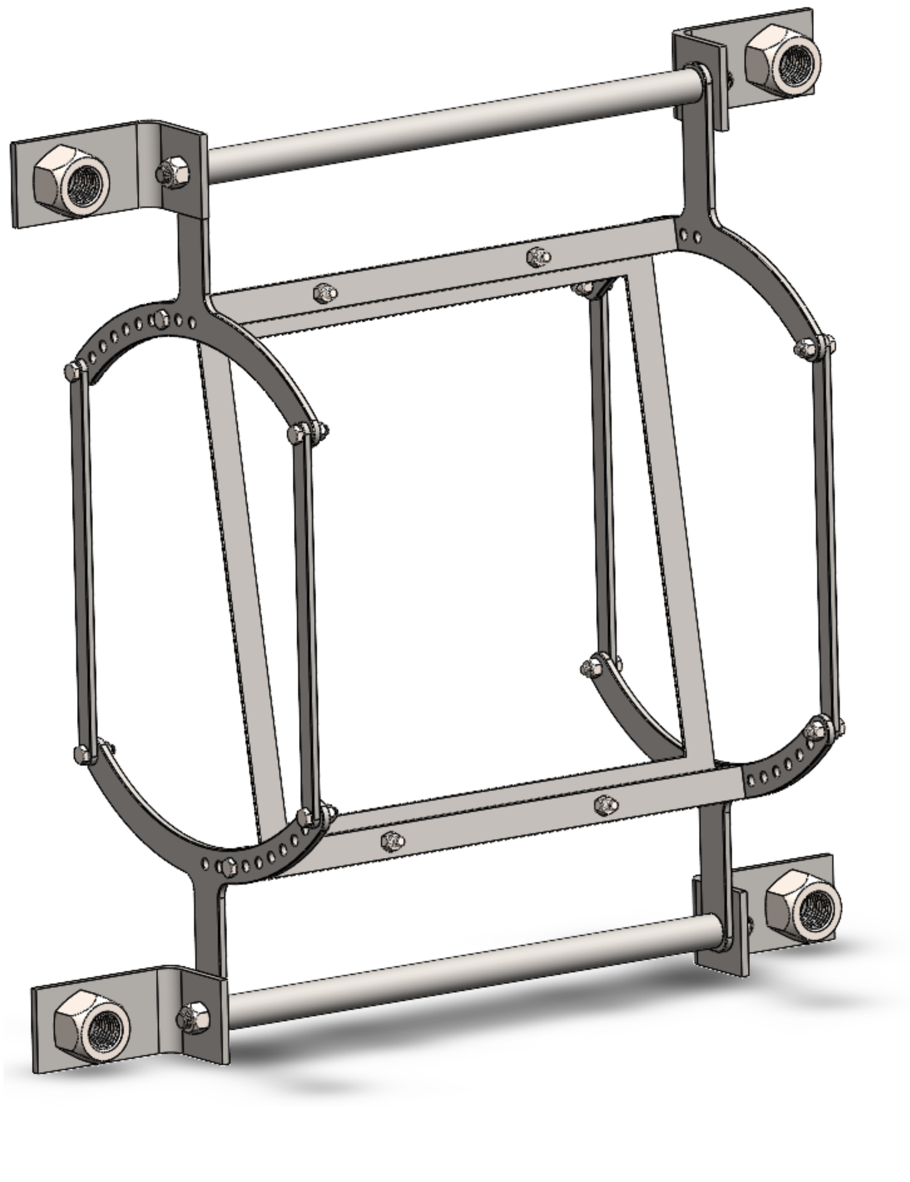
FACULTY OF ENGINEERING AND SCIENCE

Department of Materials and Production

Design of Mechanical Systems 4^{th} Semester

Student Project

Design of Flexible Ballistic Target



AALBORG UNIVERSITY
STUDENT REPORT

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Title:

Design of Flexible Ballistic Target

Project:

Design of Mechanical Systems 4^{th} Semester Project

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Synopsis:

This project aims to design an addition to the existing ballistic setup at Aalborg University. The primary purpose of the addition is to allow the angling of the target surfaces to increase the ballistic setup's testing capabilities.
The existing setup has been drawn in Solidworks to felicitate the integrated design of the addition. The addition not only serves to enable the angling of the target but has also attempted to move the point of impact into the axis of rotation to ensure more consistent testing conditions. Additionally, has the design been made focusing on ease of operability and assembly while also reducing unnecessary materials and processes to reduce complexity, weight, and costs.
The addition is manufactured primarily from $5mm$ sheet metal with limited to no bends. This is achieved through the generous use of nuts and bolts to deal with angles and connections between components.

Simulations of the effects of angling the target surface have also been experimented with. The simulations have resulted in changes to the core design of the addition. Simulations have also aided in understanding how to deal with the aftermath of the impact in catching the impact debris without damaging equipment.

Preface

This project is written by Martin Søndergaard Adelstorp at Aalborg University. It is written during the 4$^{\text{th}}$ semester of the master's program *Design of Mechanical Systems*. A thanks is given to supervisor Jørgen Asbøll Kepler whose guidance has been greatly appreciated throughout the project. Another thanks is given to Benny Endelt, who has been instrumental in simulating the different impacts.

Reading guide

This report references using the Vancouver reference system by giving a number in square brackets after a sentence, quote, or section that denotes a source found in the bibliography at the back of the report. The sources used in the project are listed in the same order as they appear in the text. The first number in a figure or table is the chapter they are in and the second number counts up as the chapter progresses.

Abstract in Danish

Aalborg Universitet har et ballistik setup bestående af en luftkanon, der kan skyde projektiler med en størrelsesorden op til $100m/s$ for et $100g$ projektil. En begrænsning ved dette setup er dog at det kun er muligt at skyde projektilet direkte på testemnet. For materiale tests der primært består af plade emner, er dette en stor begrænsning, hvis andet end direkte skyd er interessant for, hvad projektet omhandler. Denne begrænsning har ledt til dette projekt, som omhandler udvidelsen af dette setup, således at plade emner kan vinkles i forhold til projektilet.
Projektet har dermed til formål at designe en udvidelse til det eksisterende setup, der muliggør vinklingen mellem projektilet og målpladen. Denne vinkling kan opnås på flere forskellige måder, som dermed leder til flere forskellige løsninger, der kan opnå formålet. Løsningen som dette projekt endeligt designer, er baseret på konceptet, der fokusere på at flytte omdrejningspunktet for den vinklede overflade ind i projektilets bane. Dette kommer med flere fordele som at tillade det samme punkt at blive ramt ved flere forskellige vinkler, hvilket kan være meget værdifuldt ved test af diverse materialer. Dette koncept kommer dog også med en ulempe, ved at flytte omdrejningspunktet så langt fra monteringspunkterne falder den strukturelle kapacitet, så det ikke længere er realistisk at fiksere emnet. Målemnet er derfor nødt til at være tilkoblet rammen der vinkles meget løseligt for ved at simulere et ufikseret setup men også for at reducere belastningen på strukturen. Umildbart virker denne begrænsning som et stort problem, men ved nærmere eftertanke så ville det være yderest besværligt, at tilbyde et setup der er stift nok til faktisk at have et fikseret emne uden bemærkelsesværdig deformation eller slør, som begge ville varierer på baggrund af det specifikke skud. Dette er den underliggende argumentation for det koncept som løsningen er baseret på.

For at bestemme kræfterne involveret i et skud med kanonens maksimale kapacitet samt konsekvenserne af sammenstødet er der udført nogle sammenstøds simuleringer ved hjælp af programmet LS-DYNA. Disse simuleringer er baseret på et helt ufikseret målemne bestående af en aluminiums plade med en stål kugle som projektil. Stålkuglen er lavet af uendeligt stive elementer mens pladen er lavet af traditionelle lineære solide elementer.
Sammenstøds simuleringerne er lavet baseret på to variabler, pladetykkelse og vinklen mellem skudets bane og pladen. Pladetykkelsen er relevant for at bestemme kræfterne og hastighederne efter sammenstødet for forskellige stivheder, der resultere i forskellige respons. Vinklen mellem skudets bane og målpladen vil lede til forskellige resultater, og vil have et punkt, hvor kuglen ikke længere fortsætter med pladen efter sammenstødet men hopper af pladen.
Ligesom det var forventet, så viste det sig at kuglen begyndte at hoppe af pladen, hvilket kunne ses i den sidste simulering på 45°. Dette er et bevis på, at simuleringerne er vigtige i forhold til at kunne sætte tilstrækkeligt absorberingsmateriale op omkring målpladen, så intet apparatur tager skade.

For at løsningen formår at holde prisen, vægten og kompleksiteten nede, er den overordnede struktur konstrueret primært af $5mm$ pladestål, der er skåret ud ved hjælp af en digital vandskærer. Dette tillader alle komponenterne med denne tykkelse at blive skåret ud med huller fra en enkelt plade, hvormed produktionstiden reduceres kraftigt. Af de resterende komponenter er størstedelen bolter og møtrikker med nogle få komponenter fremstillet fra grunden.
Eftersom løsningen ikke altid skal tages i brug, evt. hvis en fast opspænding skal benyttes, så skal løsningen kunne afmonteres relativt uden besvær. Dette har resulteret i en løsning, hvor den første samling kan være tidskrævende, men når det kommer til afmontering, kan dette gøres ved kun at fjerne fire møtrikker fra de eksisterende gevindstænger. For at sikre at komponenterne passer sammen uden besvær, er det anbefalet at samle løsningen i to trin som angivet i løsningskapitlet.
Den endelige løsning opfylder alle de opstillede krav, og formår at gøre dette uden bemærkelsesværdigt at gå på kompromis med nogen af ønskerne for løsningen. Baseret på dette er den designede løsning vurderet til at være en succes, som kan produceres og implementeres uden at kræve eksternt maskineri eller længere arbejdstid.

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1 Introduction

The topic of ballistics is of great importance because the products developed using data and theories from ballistics range from anywhere from tennis rackets to bulletproof vests. Despite the vast amount of tests and contributions to the area of ballistics, it is still often necessary to validate the results of a simulated impact with a real possibly scaled test. It is therefore only natural that Aalborg University (AAU) would have a means of conducting ballistic tests. The ballistic setup takes the form of a shipping container that has been altered to better suit the needs of a ballistic setup. The container walls are lined with thick wooden slabs to both act as an emergency blockade for a projectile and noise reduction during testing. The ballistic setup itself consists of an air cannon which is charged from outside the container and then released using a valve next to the compressor. The target setup is made from 100x100 box section and is fixed into the floor as can be seen in figure 1.1.

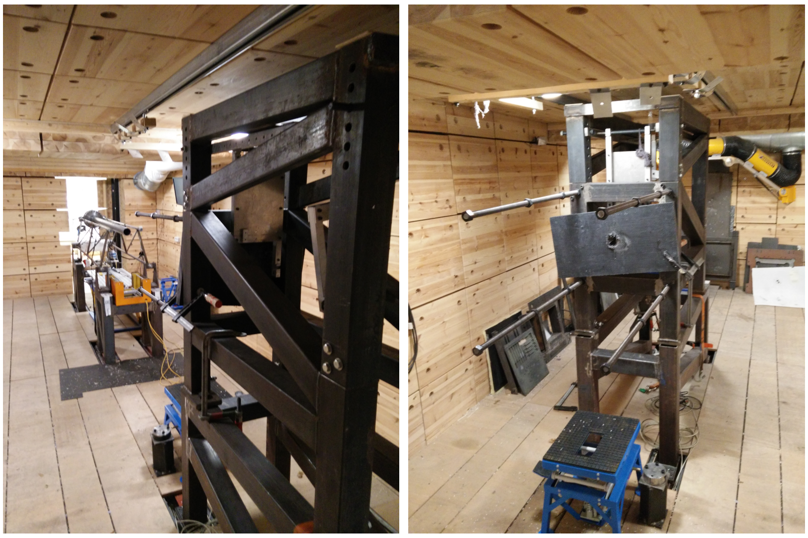


Figure 1.1: Photos of existing target setup in AAU's ballistics lab

Given that this project aims to design an addition to the existing setup, which mounts onto the front of the target setup on the threaded rods, has a structure incorporating the essential characteristics of the setup been drawn. The 3D drawing of the essential characteristics can be seen in figure 1.2. The threaded rods on the ends of the setup are screwed into plates on the inside of the box section, which on the drawing has been placed on the outside. This is to showcase the location and the supporting role it offers regarding both the threaded rods and as a surface onto which the pipes can transfer load without causing deformation of the box section.

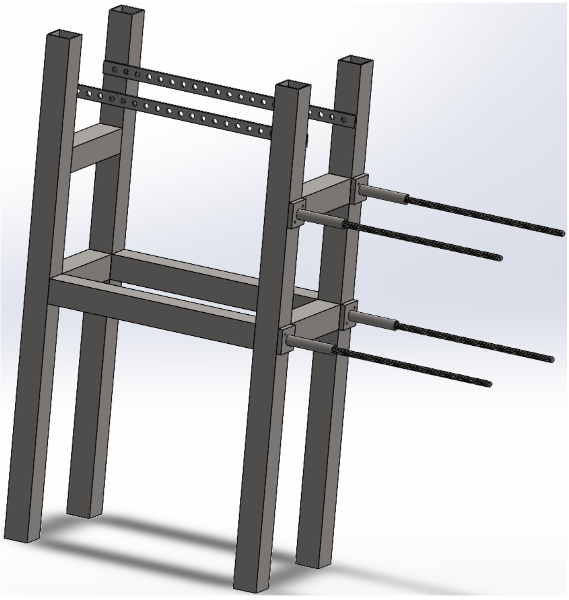


Figure 1.2: 3D drawing of existing setup

As can be seen from the photos of the setup is the air cannon placed in front of the threaded rods. This means the trajectory of the projectile is right in the middle between the threaded rods. The trajectory has also been shown in figure 1.3 by a wooden arrow.

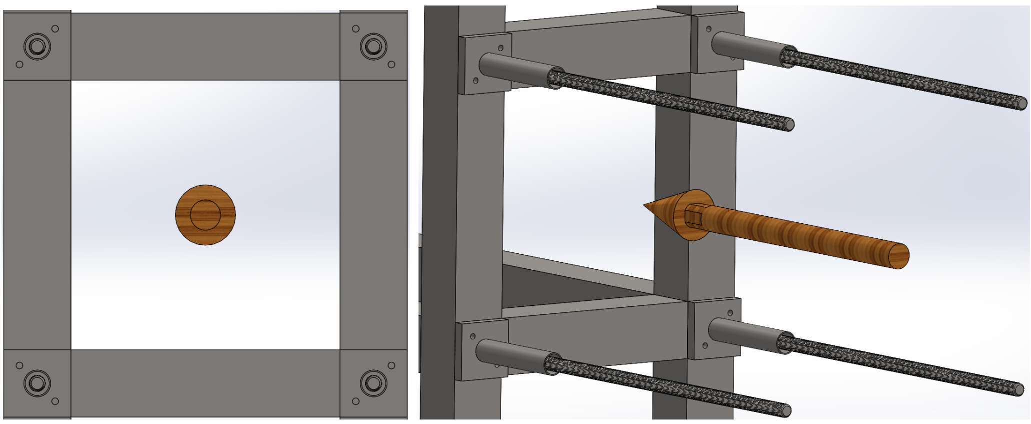


Figure 1.3: Drawn setup with projectile trajectory indicator

The project attempts to design a solution that alters the angle between the projectile and the target plates. This change in angle can be in any direction relative to the arrow as long as it follows the specifications in chapter 2.

Problem Description 2

The overarching problem of the existing ballistic setup is the inflexibility regarding the angle between the target surface and the projectile. Since the setup is functional and has been working sufficiently in the past, the project's goal is to add an extension to the setup rather than modify the setup to accommodate the requirements. This means that the solution has to be removable while still providing a suitably stable and solid frame on which the target surfaces can be mounted.
Based on the overarching description of the problem, has the specific formulation of the problem been outlined.

Design a structure for the existing ballistic setup which allows for an angled target surface

With the problem not describing a specific solution will several different concepts be developed. In order to assure that these concepts provide reasonable solutions, a series of requirements have been outlined. These are specific aspects which the concepts have to abide by.
Subsequently, has a series of goals been outlined. The purpose of these goals is to establish a means of choosing between the concepts such that the superior concept is further developed and subsequently evaluated.

2.1 Requirements

The solution's requirements are based on manufacturing, handling, lifetime, and some given specifications. Below is an overview of the requirements for the solution segmented into the previously mentioned topics. These are subsequently explained in their dedicated sections below the table.

Overview of Requirements

Manufacturing
- Utilise existing manufacturing methods at AAU workshop

Handling
- Removable
- Less than 10kg for each component

Lifetime
- Statically sustain the estimated loads
- Endure 1.000 projectile impacts

Others
- Maximum angle 90° (normal to projectile trajectory)
- Minimum angle 45°
- Minimum angle increments of 10°

Manufacturing

Since this is a standalone solution for a single structure to serve a single purpose, there are no plans regarding manufacturing outsourcing. Since the solutions to this project can take many forms, this restriction has been put in to sort out concepts that would require external equipment.

Handling

It must be possible for a single person to undertake setup and removal using standard tools. No single component may weigh more than 10 kg, and all edges must be deburred.

Lifetime

Given the following goals of cheap and easily replaceable components has very lenient requirements to the structure's lifetime. This follows the general principle of a rough solution, which can be easily repaired and failed components easily replaced in the case of a failure.

Specifications

The remaining requirements are related to the solution's performance in which angles should be possible to use with the solution. Based on the related discussion, the angles of interest have been determined as being between 45° and 90° in increments of at least 10°.

2.2 Goals

The goals for the solution build upon the requirements while also adding new restrictions for the concepts which could not be defined as requirements.

Overview of Goals

- Easy assembly and disassembly
- Easily operable
- Light components
- Cheap components
- Reduce component interference with measuring and monitoring equipment

Assembly and Disassembly

Given the previously stated desire to occasionally use the existing setup for testing, the value in a design that can relatively quickly and painlessly be removed and set up again, is very relevant.

Easily Operable

The easier the solution is to operate in regards to both physical exertion and simplicity, the better.

Light Components

This goal is a extension of the *less than* $10kg$ *for each component* requirement. This is a goal because having lighter components is better in every aspect, including the last two goals.

Cheap Components

Given the rough design philosophy stated in the *lifetime* section of the requirements is the value of cheaper components increased.

Reduce Component Interference

The most common way of extracting data from the setup has previously been to set up a camera, document the impact, and then compare it to simulations to test its validity. This approach requires a clear line of sight from the camera to the impact area; however, comparing camera data from an arbitrary angle is needlessly tricky if it is possible to observe the impact area directly from the side or above. This goal is therefore present to encourage the removal of any non-essential material around the impact area.

3 Impact Simulation

Simulating the impact of a projectile and a target plate is used for two primary reasons. Determining both the size of the loading and the way it affects the supporting structure. Additionally, once the projectile has impacted the target plate, the energy and momentum of the projectile have to go somewhere. This means that to minimize danger to the structure itself, measuring equipment and whatever else might be in the room during the test will the behavior of the components after the impact also be relevant to the final design.
The drawing of the models required for the impact simulations and the simulations themselves have been performed using the program LS-DYNA.

3.1 Setup

Since the air cannon has been used to propel anything from tennis balls to solid steel pellets, the setup chosen in the analysis is fundamental if it is to simulate what the design will be exposed to properly. For this project, the initial parameters of the setup have been chosen as a projectile with a mass of $100g$ being propelled towards the target at a speed of $100m/s$. Likewise, the projectile has been designated as a steel ball that, to adhere closely to the mass of $100g$, has a radius of $15mm$. Since the radius of the ball has been rounded up is the actual mass of the ball $110.30g$. The target is made of a single $300\text{x}300mm$ aluminum plate with different thicknesses to determine its differences in the characteristics of the impact.
As with the variety in projectiles has the target also seen significant differences in both material types and shapes. While the specific geometry of the target and how its material is defined changes, the characteristics of both the loading and the aftermath of the impact have been simplified into rectangular plates. This is done as handling different shapes and determining their effects would be outside of this project's scope and is something that would have to be evaluated when such a component is tested. Given how modern ballistic equipment is designed with a hard shell and a more ductile material underneath, is this a common thing to expect as a target. However, simulating this can vary heavily between specific materials, combinations, and conjunctions and can therefore be very difficult to model correctly. Selecting three different thicknesses of the target plate, therefore, creates a range of targets. These targets range from ones where heavy deformation and a more gradual transition is dominant to more stiff targets where only a slight indentation in the target occurs. In order to create this range, the thickness of the plates has been chosen as $10mm$, $20mm$ and $30mm$. Additionally, have two different kinds of material models been tested, namely fully elastic and a power-law model, neither of which has incorporated any

failure modes.

3.1.1 General Simulation Information

The general information is regarding the mesh for both the projectile and the plate and the modules used in the analysis. The mesh for the plate is made up of solid elements with a size of 2x2x2mm with no additional definitions given, meaning a linear mesh. Given that the projectile is a ball, the elements have been determined based on the number of elements along a given edge instead of a specific size. The solid elements of the ball have been made such that they generally match the size of the elements in the plate.
The following points describe the different modules used in the simulations and the particular reasoning, if any, that are applicable.

Materials and Parts

When defining components in LS-DYNA, both sections and materials are required. The sections define which kind of elements the part consists of in the case of this project are both components made of solid elements. To simplify the analysis has the ball been made of rigid elements, which is also a definition in the sections part of the setup.
A fully elastic and a power-law material model have been investigated to showcase further the difference between a sudden hard impact and a softer, more gradual impact. The ball is made of steel with rigid elements meaning no deformation can take place, and the material model is a simple "020-RIGID".
The plate is made of aluminum and has two different material models: "001-ELASTIC" and "018-POWER_LAW_PLASTICITY". Neither of these models has any failure modes incorporated, as correctly dealing with failed material, crack propagation, and strain rates would significantly complicate the analysis.
The materials models both utilize an E-modulus; however, where the fully elastic model only specifies the E-modulus, does the power-law model build upon it with a description of the hardening properties. The values used in the models are 68.95GPa for the E-modulus and 0.097, 0.33587 for the K and N factors; respectively. This results in the material model seen in figure 3.1, the figure also shows the fully elastic material model for reference. The values for the material models initially came from [1] but has since been validated. As can be seen on the diagram, these parameters lead to the yield stress of around 190MPa, which for an arbitrary target sample is suitable. For context is the E-modulus for aluminum also given as roughly 68GPa and the yield stress as anywhere between 35MPa and 505MPa for any given aluminum material [2].

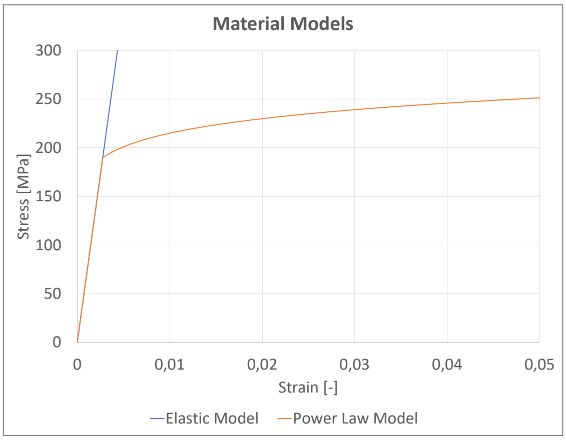


Figure 3.1: Elastic and power-law material models

Contact

The contact between the two components is handled through the "AUTOMATIC_SURFACE_TO_SURFACE" contact module, with the only additional information defined being the static and dynamic friction coefficients. Based on the values between aluminum and mild steel in [3] has the static and dynamic frictional coefficients been determined as 0.61 and 0.47 respectively.

Database

For this analysis, the properties of displacements, velocities, energies, and impact forces are of interest. In order to obtain all of these, two database modules have been used, namely "ASCII_option" and "BINARY_D3PLOT". ASCII allows for many different kinds of tracking; however, in this case, only the "RCFORC" function has been used. This function tracks impact forces in each contact from both the perspective of the slave and the master.
The D3PLOT module tracks the remaining properties, displacements, velocities, and energies. Displacements and thus velocities tracked using the D3PLOT module are done through rigid body displacement. This is equivalent to tracking the center of mass for the part, which gives good overall numbers but can overlook details in the analysis. One such detail is how the plate bends upwards on the edges during the impact; however, since most of the motion is in the downwards direction, the displacement tracked shows no sign of any upwards motion on the plate.
The energies tracked by the D3PLOT database are limited to mechanical energies, which means only the internal and kinetic energies are tracked in this project. Internal energy relates to the strains and stresses the part experiences, while the kinetic energies are based purely on the previously determined rigid body displacements and any rotation the parts experience.

3.1.2 Supported Plate

Initially, the simulation was done using two fixed support plates behind the target plate, simulating the plate being supported by the structure. Based on the forces resulting from this simulation, it is highly likely that noticeable deformation in the support structure will occur. This is even though the highest forces found in the simulation are independent of the supporting structure. Simulating the initial part of the impact with a supported test sample seems entirely possible, but getting an accurate response for the whole impact without simulating the stiffness of the components or the joints will lead to errors between simulations and observed data. Additionally, this problem behaves differently depending on both the projectile and the target as different sizes and shapes of the loading to the structure is observed.
When simulating an impact, the apparent goal is to make the simulation fit reality as much as possible. However, with a test setup, it is possible to change different factors of the test setup, which also changes the simulation. This means that the way the plate is suspended in the path of the projectile can be altered. Since whatever solution is used, some flex in joints and components themselves will happen. This is impossible to model in a simulation on which the overall design of the solutions depends.
Therefore, two options are either choosing a concept and then simulating the whole structure or fixating the target as little as possible, getting close to an unsupported setup. The first option would allow for a detailed simulation of a final solution looking at stresses and leading to a design process determining specific required thicknesses and diameters of the different components. However, it will be challenging to account for the approximations and errors as they stack up from component to component. Adding to this is that any future analyses would have to account for the same structure to model the supports accurately.
The second option gives up the functionality of a fixed setup by having a weak replaceable component fail as the target plate is affected by the impact will mean minimal loading is transferred to the structure.
The choice between these, therefore, comes down to the value of the fixed setup. Since the solution of this project is intended as a removable addition to the current setup, the value of having a fixed setup has been diminished such that an unsupported target is preferred.

3.1.3 Unsupported Plate

With the supports gone, the plate is hovering in the path of the projectile with nothing holding it in place. This means that as the projectile impacts, both parts will have a resulting velocity and, in the analysis, continue in that direction. With an unsupported setup, it is impossible to control the resulting direction fully. This means that depending on the resulting direction of the components, absorbing components, e.g., a sandbag, must be placed in the appropriate locations to catch the components after the impact to reduce the risk of damaging equipment in the lab. Thus, a new goal of the analysis becomes to determine the direction these components are moving in after the impact.

3.1.4 Angled Surfaces

With the project's primary goal being to create a structure that can angle the target surface, it is relevant to see how that affects the simulation of the impact. In order to reduce the number of simulations needed, only the 10mm thick plate has been tested at different angles.
Naturally, when the solution is implemented, it will be the target surface that rotates to the angle while the projectile's trajectory remains the same. However, it is much simpler in the simulation to simply rotate the ball's starting position and alter the velocity vector appropriately than it is to create three new plates at different angles and then run the simulation. The simulation is conducted using four different states with the ball at 0°, 15°, 30° and 45° and with the initial velocity vector changed based on the same angle.
The point which the starting position of the ball rotates around is chosen to be the center of mass for the plate instead of the original point of contact on the surface of the plate. The differences between these two can be seen in figure 3.2. This means it is the same angle, but the velocity vector intersects with the center of mass for both the ball and the plate.

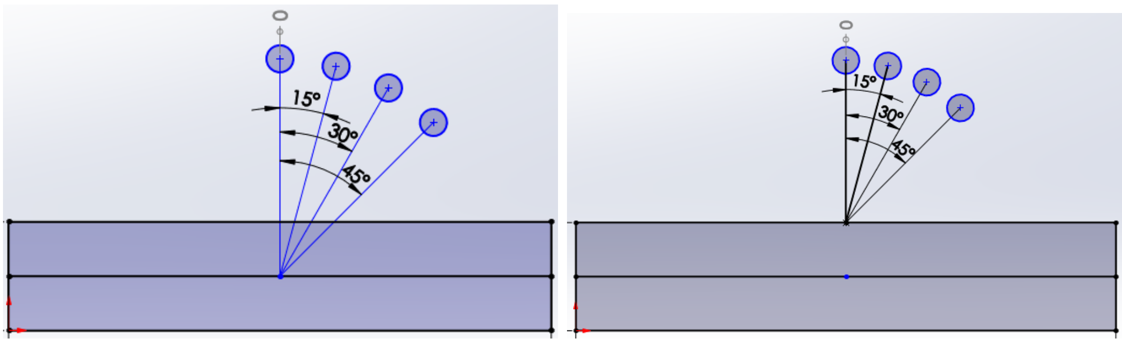


Figure 3.2: Two options for simulating the angled surface

3.2 Results

This section will cover each case of plate thickness and angled surface simulations by showing the velocities of both parts and the impact forces in the contacts. While this will show the immediate results of the simulations, the overall grasp of the results is obtained best through a video of the simulations. Because of this has each simulation had two videos, one from the side and one of the cross-section uploaded to a google drive folder here. Additionally, the folder contains all the results from the final simulations, complete with pictures, graphs, and datasheets.

3.2.1 Material Model

The fully elastic model and the power-law model have the same starting behavior. This means that for the models to show noticeable differences, the stresses in the target plates have to exceed the yield stress. The highest stress for the different plate thicknesses is between $80 - 85MPa$, which means the plates at no point exceeded the yield stress. Therefore no discernible difference between the two material models should be visible.

This is indeed the case as all the resultant graphs are so similar that there is essentially no difference between them. The only discernible difference between them is the forces, displacements, and velocities in the x and y directions. As these are so small, they are essentially errors that can appear from analysis to analysis. Given that the two material models are so similar, have their graphs been left in the previously described folder along with the results from the other simulations.

3.2.2 Normal Surfaces

In the simulation, the trajectory of the projectile has been aligned with the negative Z-axis. There is a difference between the displacements of the primary Z-axis and the two other axes of more than 1000 times perfectly reasonable. While there in the analytical case should not be any displacement, this small deformation can be attributed to slight irregularities in the mesh of either part and general numerical error in the analysis. Due to how small this deformation and accompanying velocity are regarding the primary displacement, those graphs have been pushed to the google drive folder.
A cross-section of the ball impacting the 10, 20 and 30mm thick plate can be seen in figure 3.3. The pictures of the cross-sections are taken at random times and simply show an example of the observed deformation in the given plates. An error in the simulation can be seen on the cross-section of the 10mm plate, where a portion of the plate remains undeformed and overlaps with the mesh of the ball as a result. As this only occurs for the 10mm plate when the trajectory is normal to the surface, and it seemingly has little effect on the overall results, has this result been accepted.

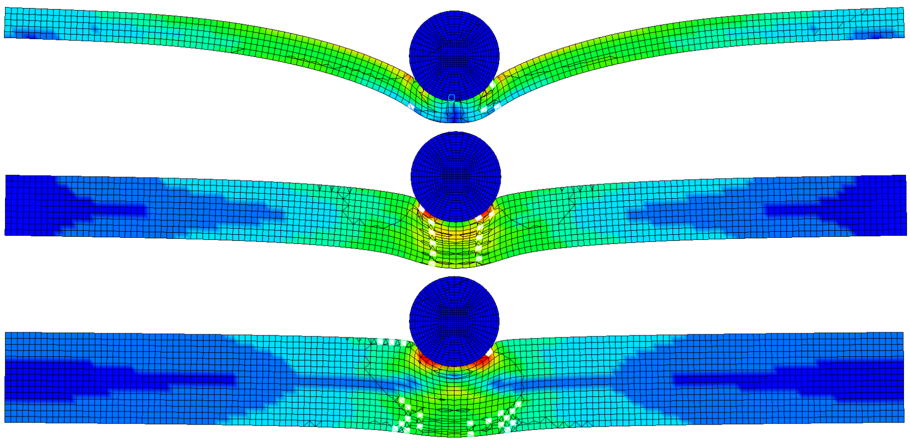


Figure 3.3: Cross Sections of the impact with 10, 20 and 30mm plates

The resultant deformation and velocity of the ball and the plate can be seen in figure 3.4. The resultant deformation and velocity signify the deformation and velocity obtained by combining the deformation or velocity in each direction into a vector. The resultant is then the length of that vector. One consequence of this is how the directional values, especially in the z-direction, may be negative but yield a positive resultant as the direction does not affect the resultant.
It can be gathered from the diagrams that the ball transfers the majority of its energy to the plate regardless of the thickness of the plate. The only two significant differences are

the amount of deformation in the plate and the speed at which the energy and momentum are transferred to the plate. The transfer speed can be seen in the differences on the "Resultant Ball Velocities" curves, where the final state of the simulation occurs after only $0,5$ms for the 30mm plate. In contrast, the ball glides more smoothly to its final state when impacting the 10 plate.

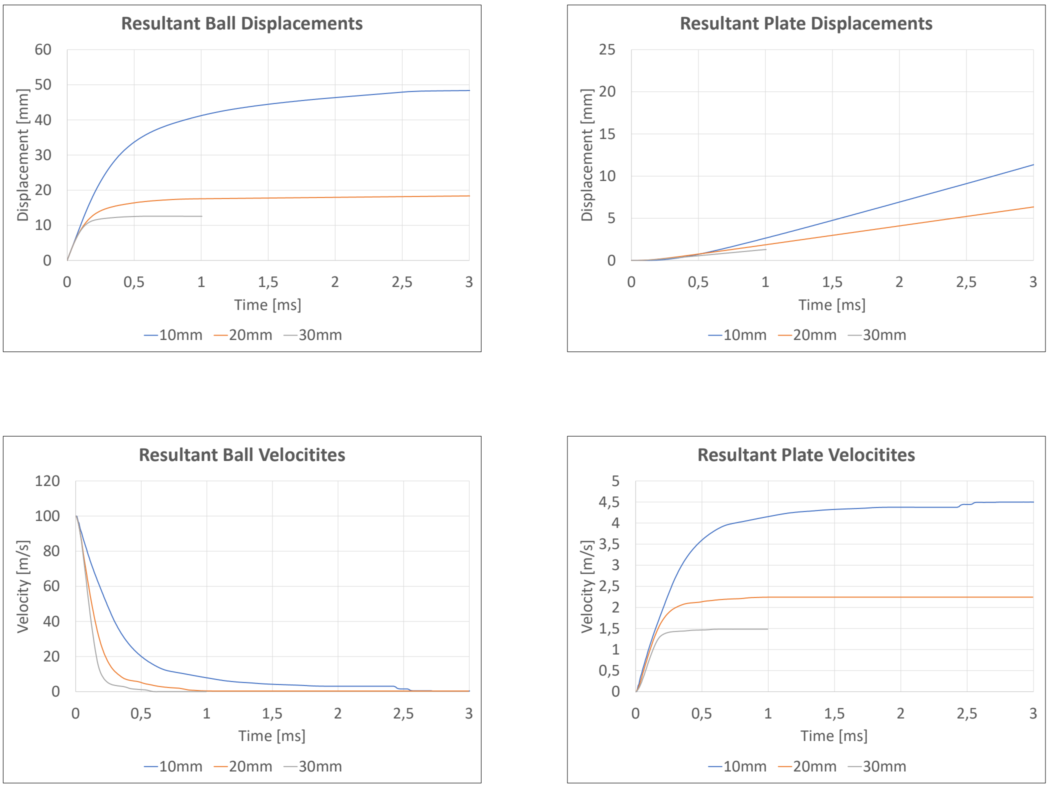


Figure 3.4: Displacements and velocities of the ball and plate with 10, 20 and 30mm thick target plates

The impact forces between the ball and the plate are shown in figure 3.5. The impact forces show the logical conclusion drawn from the more immediate impact on the 30mm plate, namely that the forces rise the quicker the impact is conducted. The small peaks around $2,5$mm are attributed to the heavy deformation which the 10mm plate sustains. The deformation is so large that it wraps around the ball, causing a small force between the two upon separation. This is also visible in the displacement and velocity graphs for both the ball and the plate.

While it is not shown on the graphs, the velocity in the x and y directions is so tiny that, as expected, the direction of movement after the impact is essentially only in the negative z-direction.

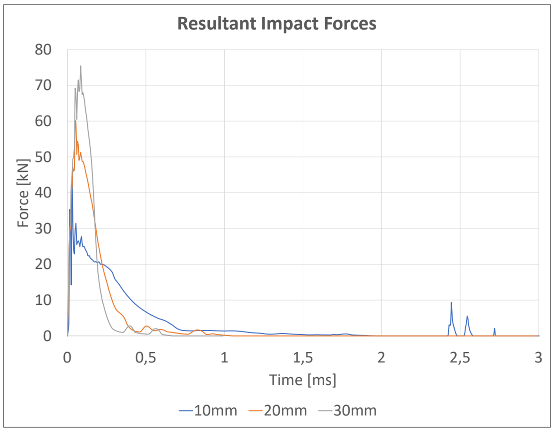


Figure 3.5: Impact forces on 10, 20 and 30mm target plates

3.2.3 Angled Surfaces

Despite how the ball got slightly lodged into the plate when impacted normal to the surface even the 15° angle is enough momentum to keep the ball going and eliminate the bump which previously kept the ball in place. This effect gets more profound the higher the angle as can be seen on figure 3.6.

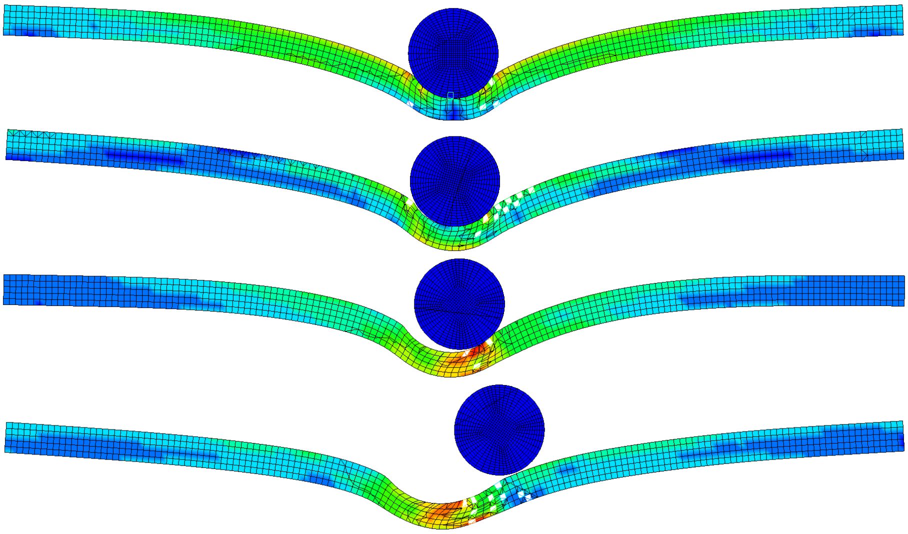


Figure 3.6: Cross Section of the 0°, 15°, 30° and 45° angles during the impact

As with the thickness, comparisons are the displacements and velocities for the different angles shown in figure 3.7. When looking at the resultant values, there is very little difference between the 0°, 15° and 30° angles. However, the step from 30° to 45° causes the ball to bounce off the plate instead of continuing with the plate, like the other angles. Additionally, the ball also has significantly more speed than the other angles after the impact, which is also reflected in the lower speed on the plate.

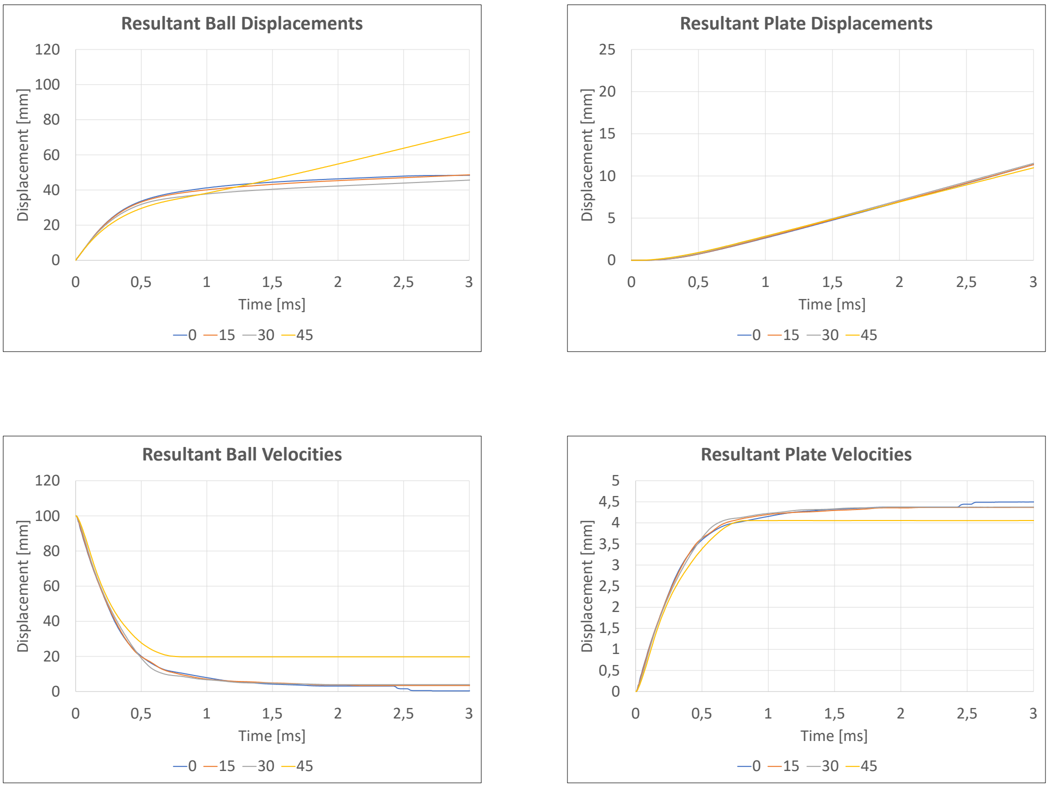


Figure 3.7: Displacements and velocities of the ball and plate angled at 0°, 15°, 30° and 45°

The impact forces associated with the different angled impacts can be seen in figure 3.8. As to be expected, with the impact of each angle lasting roughly the same time are the impact forces also roughly the same. As it could be seen on the cross-sections is only the 0° angle subject to the separation force around 2, 5ms.

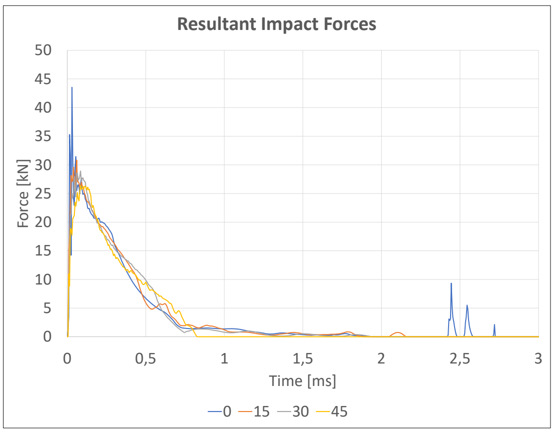


Figure 3.8: Impact forces on $10mm$ plate at 0°, 15°, 30° and 45° angles

3.3 Validation

The purpose of the validation is to make sure that the numbers obtained in the simulations are realistic compared to what would be observed in tests once the solution is implemented. The validation is based on both momentum equilibrium and the energy of the system.

3.3.1 Momentum

When looking at a closed system, the combined momentum of all the components in the system must be the same at all times. The sanity check on the momentum is done before and after the impact once the interaction between the ball and the plate has settled.
The momentum of both components is obtained by multiplying their mass with their speed. The ball's mass is calculated as the volume of a solid ball and the plate as a solid box, with the ball's volume multiplied with the density of steel and the plate's that of aluminum.

$$\begin{gathered}
V = 4/3 \cdot \pi \cdot r^3 => V_{Ball} = 4/3 \cdot \pi \cdot (15[mm])^3 = 1.41 \cdot 10^{-2}[dm]^3 \\
V = l \cdot b \cdot h => V_{Plate1} = 300[mmm] \cdot 300[mm] \cdot 10[mm] = 0.90[dm]^3 \\
V = l \cdot b \cdot h => V_{Plate2} = 300[mmm] \cdot 300[mm] \cdot 20[mm] = 1.80[dm]^3 \\
V = l \cdot b \cdot h => V_{Plate3} = 300[mmm] \cdot 300[mm] \cdot 30[mm] = 2.70[dm]^3 \\
m = V \cdot \rho => m_{Ball} = 1.41 \cdot 10^{-2}[dm]^3 \cdot 7.8[kg/dm^3] = 110.27[g] \\
m = V \cdot \rho => m_{Plate1} = 0.90[dm]^3 \cdot 2.69[kg/dm^3] = 2.42[kg] \\
m = V \cdot \rho => m_{Plate2} = 1.80[dm]^3 \cdot 2.69[kg/dm^3] = 4.83[kg] \\
m = V \cdot \rho => m_{Plate3} = 2.70[dm]^3 \cdot 2.69[kg/dm^3] = 7.25[kg]
\end{gathered} \tag{3.1}$$

Given that the speed of the ball is always $100[m/s]$ and the speed of the plate is always $0[m/s]$ regardless of setup is the starting momentum is always the same.

$$p = m \cot v => p_{Ball} = 110.27[g] \cdot 100[m/s] = 11.03[kg \cdot m/s] \tag{3.2}$$

With the speed of all three plates being $0[m/s]$ the resulting momentum is $0[kg \cdot m/s]$.
As the ball and plate each have different speeds after each impact on the three different plates has the data been shown in table 3.1. Additionally has the change in momentum as well as the loss in momentum been noted.

Thickness								
		Start		End				
Name	Test	Speed	Momentum	Speed	Momentum	Change	Loss	
[-]	[-]	[m/s]	[kg·m/s]	[m/s]	[kg·m/s]	[kg·m/s]	[kg·m/s]	[%]
Ball1	10mm	100	11.03	0.41	0.04	-10.98	0.12	1.08
Plate1		0	0.00	4.50	10.86	10.86		
Ball2	20mm	100	11.03	0.40	0.04	-10.98	0.15	1.32
Plate2		0	0.00	2.24	10.84	10.84		
Ball3	30mm	100	11.03	0.07	0.01	-11.02	0.27	2.45
Plate3		0	0.00	1.48	10.75	10.75		

Table 3.1: Momentum for ball and plate before and after the impact in the thickness tests

As seen in the results section on figure 3.5 and 3.8 has the forces observed in the impact also been noted. While these forces play a part in the momentum equilibrium, they by

definition have to act equally on the plate and the ball; hence they cancel each other out in the equilibrium. Due to this, it is acceptable to simply look at the resulting speeds and masses after the impact.
As previously mentioned, should the total momentum before and after the impact remain the same. However, given that a loss is observed, see table 3.1, this is not true. Given that this difference in total momentum is within 2.5%, it is fair to assume this is simply an error in the simulation.
In the same way as for the thicknesses has the momentum for the balls and plates in the angled simulations also been noted in table 3.2.

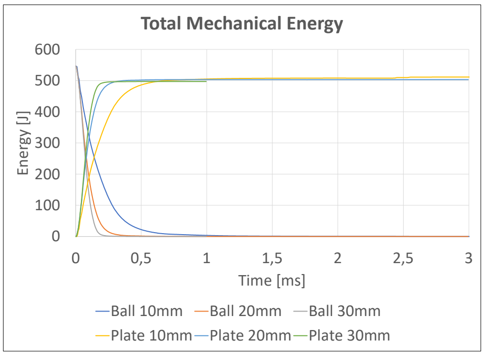
Angle								
		Start		End				
Name	Test	Speed	Momentum	Speed	Momentum	Change	Loss	
[-]	[-]	[m/s]	[kg·m/s]	[m/s]	[kg·m/s]	[kg·m/s]	[kg·m/s]	[%]
Ball1	0°	100	11.03	0.41	0.04	-10.98	0.12	1.11
Plate1		0	0.00	4.49	10.86	10.86		
Ball2	15°	100	11.03	3.44	0.38	-10.65	0.10	0.89
Plate2		0	0.00	4.37	10.55	10.55		
Ball3	30°	100	11.03	3.97	0.44	-10.59	0.02	0.17
Plate3		0	0.00	4.37	10.57	10.57		
Ball4	45°	100	11.03	19.76	2.18	-8.85	-0.95	-8.62
Plate4		0	0.00	4.05	9.80	9.80		

Table 3.2: Momentum for ball and plate before and after the impact in the angle tests

As expected are the values for the 0°, 15° and 30° within a perfectly reasonable range to be attributed to a combination of error and the loss in accuracy accompanied by using the center of mass for the velocity value. However, the -8.62% loss for the 45° angle cannot be explained this way as a negative loss means more momentum has been introduced during the simulation. Thus, the 45° angle cannot be relied upon as much as the other results. To which degree this mismatch in the momentum equilibrium affects the results is unknown, and thus the precision or the general behavior cannot be accounted for.

3.3.2 Energy

The energy validation is similar to the momentum validation in that satisfying the equilibrium is required in a closed system. The primary difference is the increase in the number of sources for energy compared to momentum. Despite this, only mechanical energy, which is the internal energy and the kinetic energy, has been noted for both the ball and the plate. Given that the ball is made of rigid elements, can no deformation and, therefore, strain occur within the ball. The internal energy is determined through strains and stresses; thus, the internal energy of the ball will always be $0[J]$.
The mechanical energy for the ball and the plate in both the thickness and angle simulations are shown in figure 3.9.



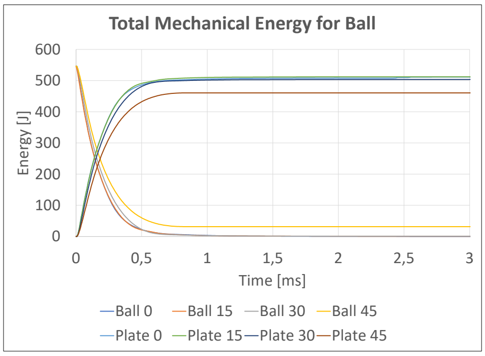
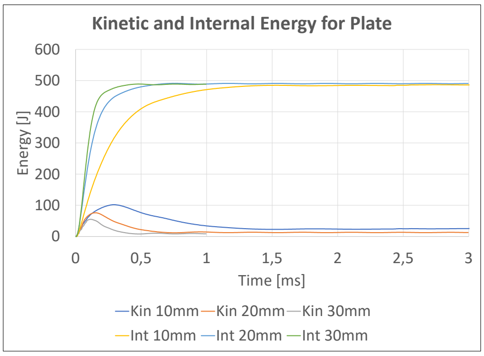


Figure 3.9: Total mechanical energy for the ball and plate in the thickness and angle simulations

Looking at the graphs, the same conclusion for the thicknesses arises with the thicker plates having a quicker transfer of energy than the 10$[mm]$ plate. The only graph which deviates from the norm is the plate angled 45° where the ball keeps a noticeable amount of kinetic energy.

From the graphs, it can be seen that they all have a very similar amount of energy remaining after the impact. This remaining energy is an average of 7.77[%] for the three thicknesses, and 7.53[%], for the four angles, lower than the starting energy for the ball. With only the mechanical energy noted in this project, the energy difference is attributed to other forms of energy. In the case of an impact, this would primarily be thermal and frictional energy, where frictional energy dissipates into thermal energy as the impact occurs. In the analysis, no coefficients for the thermal characteristics of the materials have been stated. Because of this, has the energy difference been attributed purely to friction or some standard parameters LS-DYNA specifies for the "AUTOMATIC_SURFACE_TO_SURFACE" contact or the material models.

The energy distribution between internal and kinematic for the plates in both simulations are shown in figure 3.10. These graphs show that initially, the dominant energy in the plate is kinematic; however, as the ball and surrounding area of the plate slow down and the plate absorbs, the energy in the form of deformation is the internal energy rising. The internal energy eventually becomes the vastly dominating energy in the plate with an average of 96.99% for the three thicknesses and 95.39% for the four angles.



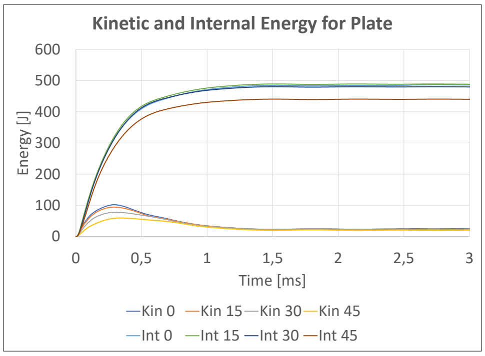


Figure 3.10: Mechanical energy for plate broken into internal and kinematic

3.4 Conclusion

With both the momentum and energy validations being within reasonable limits, have the simulations been judged as serviceable. Given that the simulation does not account for gravity due to the small time frame, are the resulting directions only applicable right after the impact. This means that the further the stopping material is placed from the impact, the higher the deflection from the simulated exit direction will be. The exit directions for both the ball and plate are shown in table 3.3 in the form of angles relative to both the trajectory of the ball and the horizontal plate. A picture showing the meaning of both angles can be seen in figure 3.11.

	Ball		Plate	
	Angle Relative to		Angle Relative to	
Test	Trajectory	Horizontal	Trajectory	Horizontal
0	19.94	-70.07	0.01	-89.99
15	17.20	-57.80	0.60	-75.60
30	38.15	-21.85	2.39	-62.39
45	54.00	9.00	10.24	-55.24

Table 3.3: Angles of ball and plate after impact relative to starting trajectory and horizontal plane.

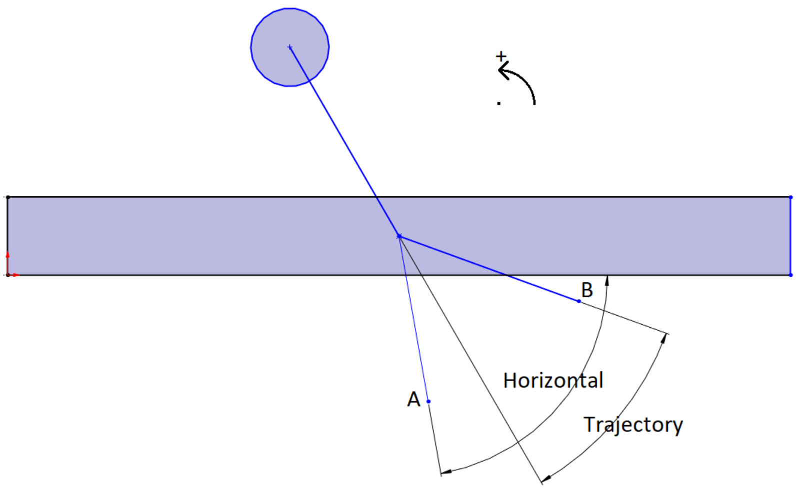


Figure 3.11: Explanation of the two angles given in table 3.3

The exit angles are essentially as expected, with the ball gradually increasing its exit angle as the entrance angle increases. The ball, when hit straight on with angle 0° has a noticeable angle when in theory, it should just be going straight up or down after the impact. This is simply due to the ball moving so slowly that the minor errors or variations in the x and y directions become relevant. This can be seen as the speed of the ball is $0.01m/s$ in x, -0.08 in y, and $-0.40m/s$ in z after $5ms$ of simulation. The resultant speed of the ball increases with the angle to yield $0.4m/s$, $3.44m/s$, $3.97m/s$ and $19.76m/s$ for the 0°, 15°, 30° and 45° angles respectively. The behavior of the plate also seems reasonable as it gets more and more horizontal velocity the higher the entrance angle of the ball.

Concepts 4

Based on the problem description and the conclusions from the impact simulations, a series of different concepts have been proposed. The concept on which the solution for the project is based is presented and described in this chapter, while the alternative concepts can be seen in the appendix. The construction of these concepts has been done throughout the impact simulation, meaning some of the concepts are targeted towards sustaining loads of the impact instead of simulating an unsupported testing setup.
Subsequently is the justification in the choice of which concept the solution is based on.

4.1 Rotating Frame Concept

This concept relies on a support structure that moves the mounting points for the target frame from the four threaded bars closer to the middle. This concept moves the axis which the target frame rotates around directly into the path of the projectile. This means that the projectile will always hit in the center of the target frame regardless of the selected angle. A 3D perspective drawing along with a side view of the concept can be seen in figure 4.1 and 4.2.
Given the support structure needed to move the point of rotation has this concept been limited to the reduced loading scenario where a unsupported plate is tested.

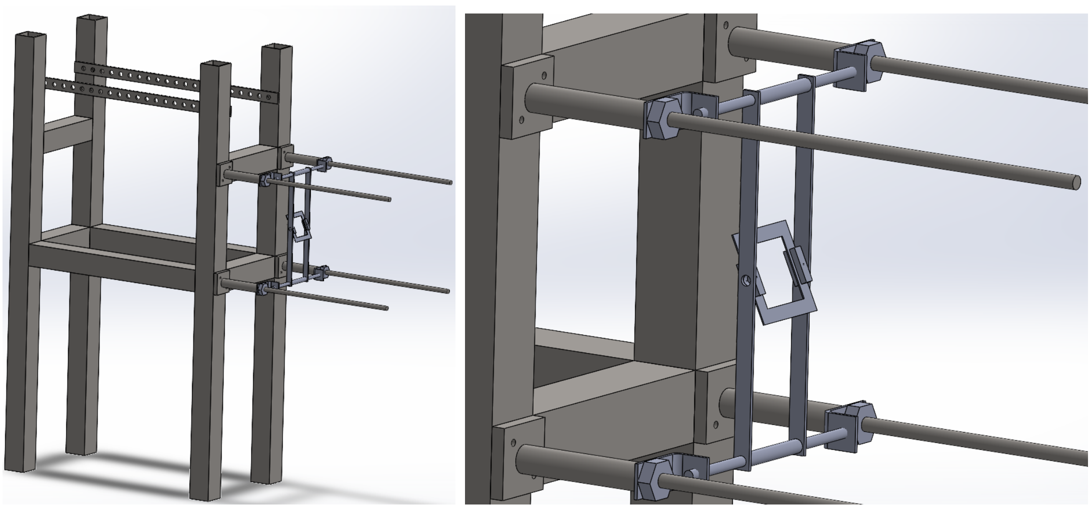


Figure 4.1: 3D perspective drawing of the rotating frame concept

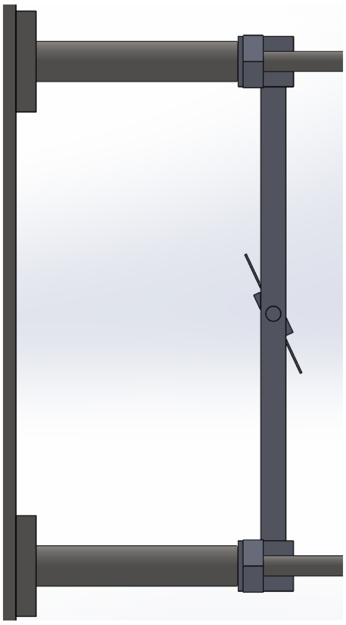


Figure 4.2: Side view of the rotating frame concept

4.1.1 Inner Frame

The concept uses a pin on either side of the target frame, which is supported by two pieces of steel mounted at the bottom and top close to the threaded rods. Having these two pins allows for the target frame to be mounted onto the pins, which they rotate around. The pins can then either be straight cylinders to reduce friction or bolts to simplify mounting and better secure the specific angle leaving less stress on the mechanism which sets the desired angle.

The inner frame is something on which the target plate is mounted onto before entering the laboratory. This results in a more flexible solution with several different ways of mounting the plate to the frame, e.g., tape, string, or friction. The frame then has the necessary design such that it is securely attached to the setup allowing the plate to fly after the impact. The inner frame simply has to support the target plate at the given angle, meaning it can be very frail compared to the remaining structure. An example of the inner frame can be seen in figure 4.3.

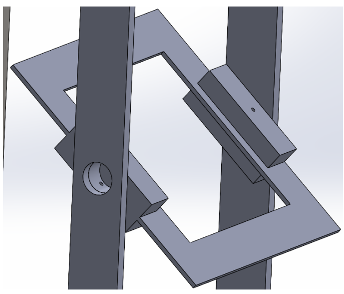


Figure 4.3: Inner frame example for the rotating frame concept

Angle Specification

In this depiction of the concept, no angle selection method has been chosen, although this can be done in a few different ways.
Firstly a bracket with holes for different angles can be mounted to the support structure. The inner frame can then either rest on the selected hole or fixated to it.
Alternatively, can the pins be changed for bolts, and by threading the inner frame, can the bolts place the frame in a certain way before tightening the bolt on either side.
The reverse of this is also possible where the support structure is threaded, and a small hole is drilled in the bolt allowing a tiny locking needle to pass through and locking the angle between the bolt and the frame.

4.1.2 Cross Rods

While the inner frame technically does add some rigidity to the solution, allowing it to support itself and the plate, how easy it is to operate is significantly increased by adding a cross rod between the threaded bars on the top and the bottom. Additionally, this adds to the overall strength of the solution and simplifies the assembly as mounting components to the cross rods and then putting them on the threaded rods is much simpler than the alternatives.

4.2 Comparison

The concepts have all been developed with the requirements and goals in mind. As such, any concept can overcome all of the requirements. Given as the goals are not specific borders to cross but more like guidelines for a good solution, have each concept been valued against each goal as can be seen in table 4.1. This is done to display the strengths and weaknesses of each design regarding a given goal.

	Assembly	Operable	Weight	Cost	Interference
Manual	5	2	6	5	5
Swing + Frame	2	6	4	3	5
Swing + String	2	6	4	4	5
Rotating Frame	3	7	5	3	4

Table 4.1: Concepts valued against each goal

Choosing which concept the solution is based on is not based on a numerical score for each concept. The solution concept is therefore chosen based on various advantages and disadvantages of the specific concepts.

4.2.1 Assembly

While the assembly for the swings is simple, they also require either fiddling with the string or mounting the frame. The frame's mounting is very similar to the steps required to assemble the structure for the rotating frame. The rotating frame has scored slightly better due to it not using a shaft which, while simple to mount, requires managing both

the frame and the shaft during assembly. The rotating frame can easily be segmented out and partially assembled before putting it on the existing structure resulting in a very flexible assembly process.
The manual concept has the best score due to its simplicity both regarding the way things fit together and the number of components in general.

4.2.2 Operable

While the manual concept accomplishes the requirements, dialing in the specific angle is a very tedious process. This is the case whether calculating the distance it should be moved and measuring it out or measuring the angle directly. Additionally, having to ensure the projectile's trajectory is vaguely in the middle by adjusting the height of the target frame is equally time-consuming.
All the other concepts are more user-friendly, fixing the previous issues entirely or introducing slots that can be efficiently utilized without measuring or calculating the resulting angle during the setup.

4.2.3 Weight

Both the swing concepts rely on a solid steel shaft to rotate the target frame around, which significantly increases the weight of the concepts. This can be alleviated from what is depicted in the concepts; however, the purpose of the swings is to felicitate the different angles and ensure the movement of the structure after the impact. The latter purpose has a lot less value if the primary use case is a free setup where the movement of the frame is negligible.
The manual concept requires the largest frame, but this is most likely counteracted by reducing components required for mounting hence why it has gotten the highest score.

4.2.4 Cost

With the manual concept winning the weight goal and consisting of the least number of components, is it no surprise that it also has the highest score when looking at the cost. However, it is only slightly ahead of the others due to the possibly higher tolerances regarding the sliding mechanism and joints next to the mounting points. The string concept is next due to a similarly low amount of components compared to the other two leaving them last with the most components and material used.

4.2.5 Interference

Here everything scored the same except the rotating frame as the others only have the thickness of the frame in the area surrounding the impact. However, the rotating frame concept has the mounting points located in this area and therefore blocks some of the views of the impact. This problem can be alleviated while still keeping the inner frame and the centralized axis of rotation.

4.2.6 Choice

In general, is the swing mechanism only of relevance if the impact is fixated and absorbing the impact into the structure is a priority. Since this is not a priority, these two concepts fall behind the others due to their unnecessary bulk and rigidity. Comparing the manual and the rotating frame concepts, the deciding factor becomes operability. In comparison, the manual concept is more straightforward and has the highest flexibility both in the possible angle increments and the possibility to angle it to the side; the fact that for each use turning the bolts and measuring out the angle or distance is tedious and unnecessary.

Solution 5

The final solution designed based on the rotating frame concept can be seen from different perspectives in figure 5.1. This chapter serves to document the changes from the concept to the final solution while also describing the consequences of the design.

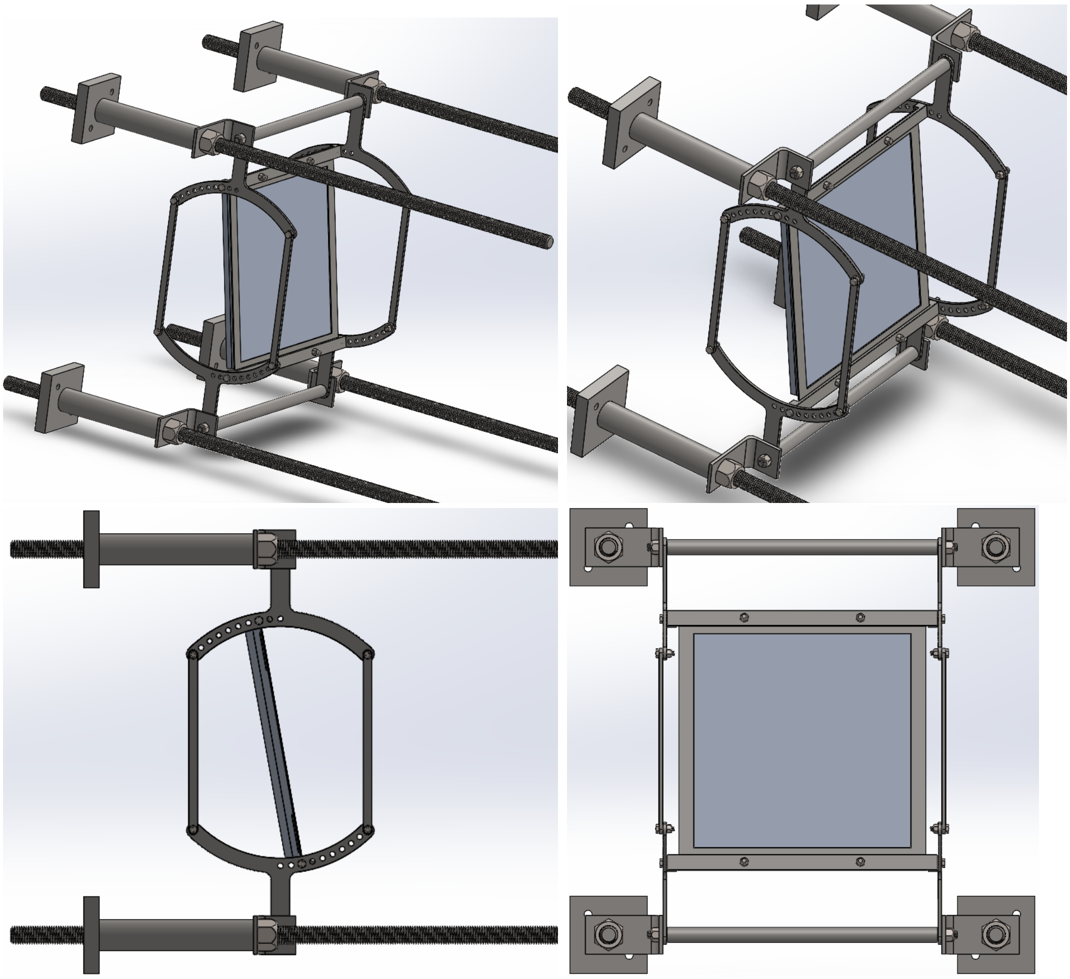


Figure 5.1: Final solution seen from different perspectives

5.1 Concept Refining

Following the choice of the overall concept is the more detailed design of the concept, which is based on the requirements and goals of the solution. The most glaring of these aspects is the rotation mechanism, as this is changed noticeably from the original concept to the final design. However, there also several general changes required for the final design to be a valid solution.

General Refining

Moving from the concept to the solution entails determining and specifically defining materials and geometries and any external components like nuts and bolts. With the support structure of the solution consisting primarily of sheet metal, the thickness of these components has been kept the same to simplify manufacturing at a small cost to material requirement. These sheet metal components are the angle plates and the support strips and can be seen in figure 5.3.

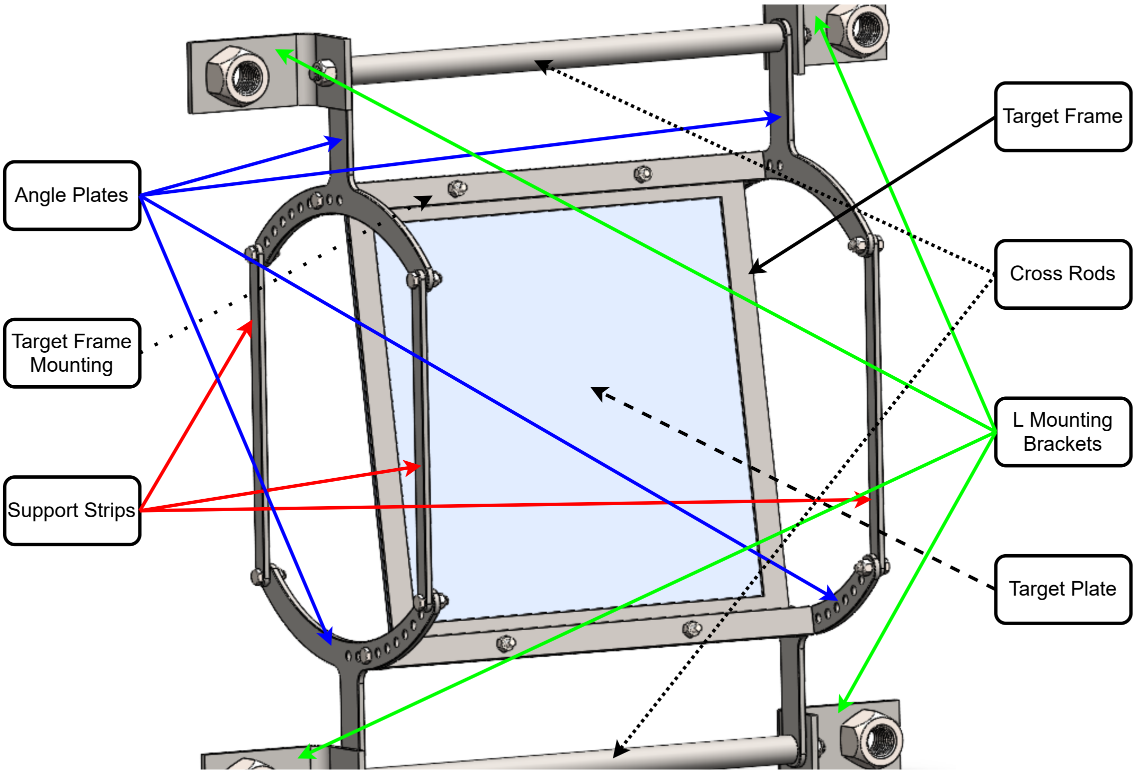


Figure 5.2: Names of manufactured components

The remaining manufactured components are the cross rods and the components used in mounting the target frame. This leaves the components which are bought as manufacturing them is inefficient with regards to both time and cost. These components are the nuts and bolts which hold the structure together. A list of the nuts and bolts required for the solution can be seen in table 5.1

Bolts				
Size	Pitch	length	Thread Length	Number
M6	1mm	20mm	20mm	12
M6	1mm	12mm	12mm	4

Nuts		
Size	Pitch	Number
M6	1mm	12
M10	1,5mm	4
M24*	3mm*	4

Table 5.1: Nuts and bolts used.
* Assumed specifications of threaded rods

Rotation Mechanism

Reducing the interference the solution has on any measuring or monitoring equipment is the driving motivation for change in the rotation mechanism. One of the aspects this goal affects is how observable the target is from the top and especially the side. In the original concept, the axis of rotation for the target frame goes straight through the projectile's path by having a pin on either side. The frame then rotates around these pins to select the given angle. This is the simplest solution in placing the axis of rotation in the path of the projectile. However, this can be done in other ways. Keeping the axis of rotation while moving the mounting points is the aim here, as this will remove any necessary geometry from the area around the axis of rotation.
The manual concept mounted the frame to each threaded rod and rotated the target frame to the given angle using these four mounting points. Implementing these four mounting points onto the design while keeping a centered rotating frame and the ability to select a given angle has led to the following design for the rotation mechanism.

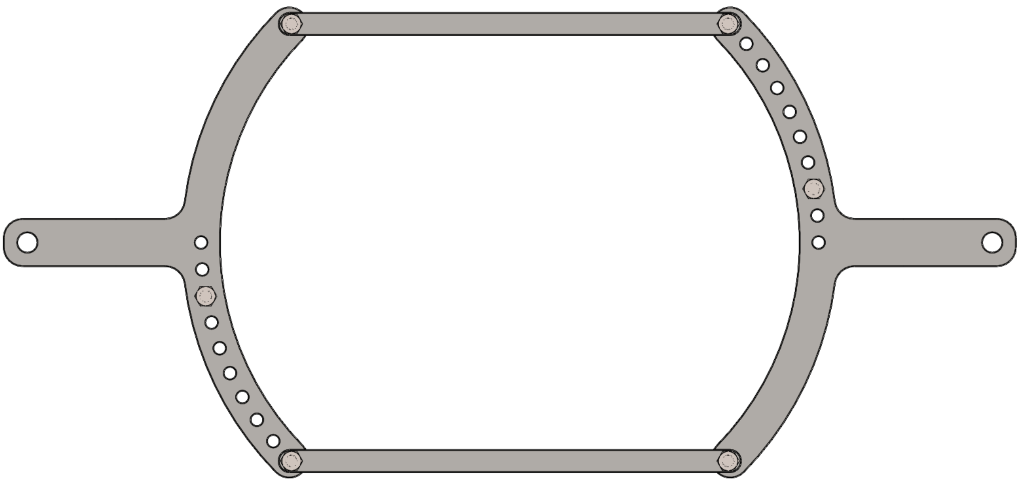


Figure 5.3: Half of the rotation mechanism placed horizontally

This rotation mechanism moves the mounting points for the target frame to the four corners of the frame and uses the same mounting points to select the angle. This means that the requirement for the supporting structure to overlap the point of impact is removed and replaced with a circular geometry. This change increases the complexity and the material requirement of the solution but provides a much clearer view of the impact.
From a structural perspective is this solution also an improvement as the load is now distributed over the four corners instead of the two middle pins. This both reduces the required strength of the joints and moves them closer to the threaded bar causing more of the load to go through the target frame instead of the support structure.
The holes used to select the angle of the target frame are placed 5° apart, and as this is done for both the top and bottom mounting points will the target frame have an equal change in angle. This means that at least 15 different angles are possible.

5.2 Materials, Production, and Assembly

With the final solution designed, can the list of materials required, production methods, and assembly procedure be specified. This section is built up around the components and has both their materials and production described while leaving the assembly process to the end.

5.2.1 Sheet Metal Components

For the components manufactured out of sheet metal, can these be grouped and produced from the same sheet of steel. Creating these components from the same sheet of steel allows them to efficiently be cut using either a plasma or water jet cutting table where the schematic of the cut out can be uploaded to the machine. This is heavily beneficial as the sheer amount of holes in these components makes producing the components by hand inefficient. With this in mind has an example of a cut out been proposed and shown in figure 5.4. With the components arranged as shown in the figure, can all the components be cut out from a single 300x700mm piece of 5mm thick steel. Due to the shape of the angle plates, the amount of waste material is relatively high, with only 30% of the material being used for components. The primary way this could be alleviated is by segmenting the angle plates into two individual components and joining them either by welding or with bolts, but this has been judged as excessive compared to the gained material efficiency.
Using a plasma or water jet cutting tool also allows for cutting the holes, which means the only work left after the cutting process is refining the edges of the components. For the holes, this entails countersinking the sides while the sides of the components can be refined using a belt sander.

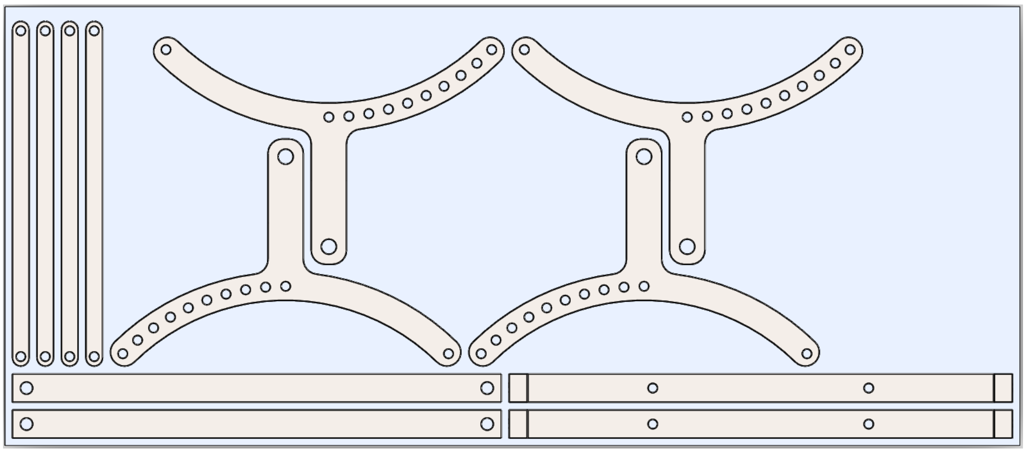


Figure 5.4: Example of cutout setup

5.2.2 Cross Rods

The cross rods, shown in figure 5.5, serve to both ease the assembly process and stabilize the structure, especially when the target frame is not mounted. Given that the cross rods need male threading on both ends, are there two methods to manufacture this component. The most obvious one is a solid cylinder whose ends are machined down and then threaded

using a die on the lathe. An alternative approach is to cover a threaded rod with a thick-walled pipe. Both of these solutions produce a component that lives up to the requirements; however, the second option allows the entire setup to slide to either side depending on the precision of the tightening of the nuts on the ends. As a result, has the first option with a machined cylinder been chosen.
This means the materials required for the cross rods are a single 20 cylinder with a length of 800mm or two 400mm cylinders. The diameter of the cylinder may seem excessive but as it is a central mounting point for the rest of the solution has this thickness been chosen.

Figure 5.5: Cross rod

5.2.3 Target Frame Mounting

As previously described is the target frame-mounted using four bolts through the angle plates into two brackets. These brackets are what the target frame is mounted onto using the bolts in the middle seen in previous figures. The bracket shown in figure 5.6 consists of a plate which is also seen on the cut-out example in figure 5.4 with two $9x13x20$ bricks welded to the plate. The offset between the hole and the plate and subsequently also the two bricks is to align the center of the target plate with the axis of rotation. If this had simply been a thick plate or a cylinder with two holes for the bolts, would the target plate have been moved from the axis of rotation by the thickness of the target frame. Depending on the precision needed, this could prove annoying to deal with for specific applications. That solution has been chosen for the official drawing; however, more straightforward alternative solutions have been suggested in later sections of the chapter.
The materials required for this are partially accounted for with the material designated to the cut-out in the sheet metal components section. The additional material needed is the two bricks, which can be scavenged from the other processes or cut of a rod with similar dimensions.

Figure 5.6: Target frame mounting bracket

5.2.4 Target Frame

The target frame is fixed with its mounting brackets and serves to align and hold up the target plate. Since this component sustains essentially no load even compared with the other components in the solution while also being significantly bigger, this component has not been made from the same thickness of steel that the sheet metal components have. Conversely, this has been made of thinner 2mm steel
Additionally, cutting it out in a single component like the other sheet metal components is unnecessarily wasteful because of the size. The manufacturing method of choice is to initially tap weld four individual pieces together to form the desired shape. While it is

reasonable to cut these plates in the same manner as the other sheet metal components with a plasma or water jet is the thickness of these more realistic to manufacture manually. The cut-out drawing has been made to signify that without holes as these are then drilled later.
Since the target frame also aligns the target plate, small strips of metal have been welded to two of the four plates each to assist the tap welds in holding the target frame together. This manufacturing method culminates in two 320x30mm and two 280x20mm plates with a thickness of 2mm for the base frame and six 50x5mm strips of metal. To save on material, these strips can be cut from the same piece of metal as the larger plates, as shown in the cut-out example in figure 5.7.

Figure 5.7: Target Frame and example cut out of materials for it

5.2.5 Brackets

The only components left are the brackets between the threaded rods, and the cross rods, a drawing of these can be seen in figure 5.8. As the shape of these brackets are straight, 90° bends are it entirely possible to find useable brackets in the same manner as the nuts and bolts. These would most likely need new holes drilled to fit both the size and location requirements of the brackets. If it is impossible to find, then simply drilling a Ø24 and Ø10 hole before bending a 100x50x5mm piece of steel will provide a suitable replacement.

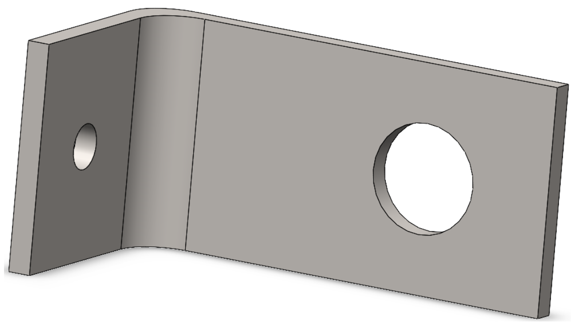


Figure 5.8: L mounting bracket

5.2.6 Total Bill of Materials

Adding up all the materials from each component yields the materials seen in table 5.2. This list exempts the materials for the L brackets as they are assumed to be obtained either as bought components or manufactured from a plate or a piece of angle iron.

Type	Material	Dimensions
[-]	[-]	[mm]
Plate	S355	700x300x5
Plate	S355	330x135x2
Cylinder	S355	Ø20x800

Table 5.2: Raw materials required [4]

5.2.7 Assembly

The assembly process can be split into two sections. The first section is the assembly of the top and bottom parts of the solution. All the top and bottom components can be mounted to the cross rods with only two nuts. This is then done loosely to allow proper orientation in the second section of the assembly process. The second section contains what remains and involves sliding the top and bottom over the threaded rods, fixing them with the $M24$ nuts, and using the support strips securely mount them into position. The first assembly process is shown in figure 5.9 with the second process being broken up into two parts, for the sake of clarity, in figure 5.10 and 5.11.

Figure 5.9: First section of assembly process

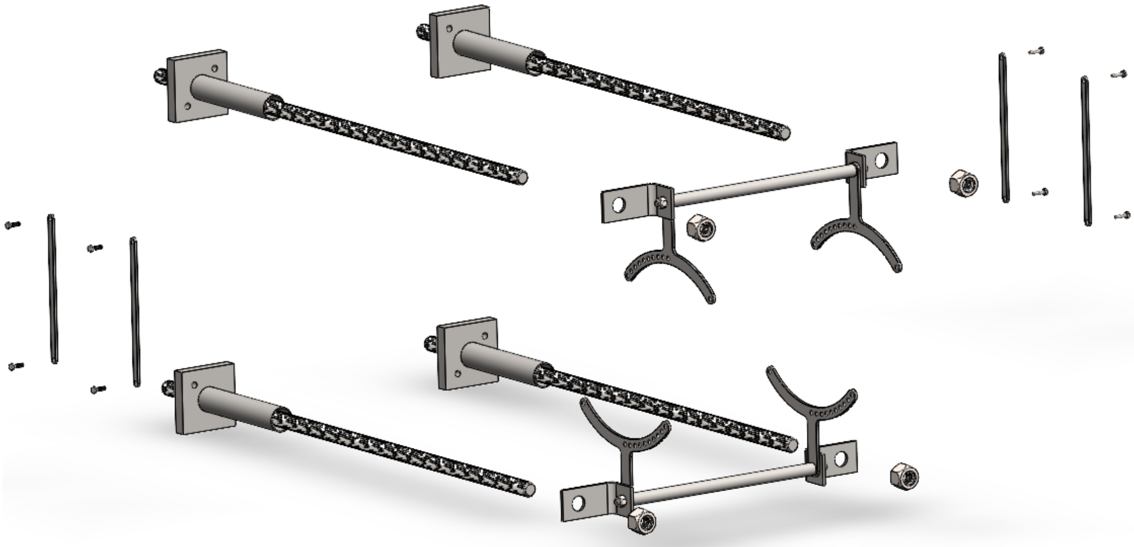


Figure 5.10: First part of the main assembly process

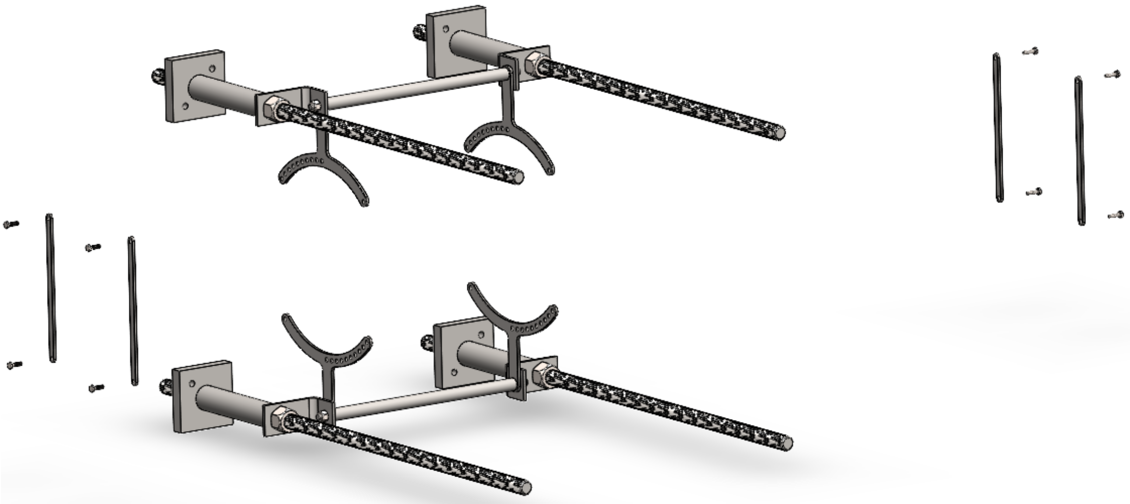


Figure 5.11: Second part of the main assembly process

5.3 Potential Changes

How the target frame is mounted has deliberately been made flexible to accommodate alternative methods of mounting both the target frame and the target plate itself. This is a consequence of the verity with which the targets take shape. The method of mounting the target plate used in the solution has been chosen as it offers the greatest precision the setup can provide. However, fastening every bolt and even using the mounting bracket for the target frame can be unnecessary and cumbersome for specific applications. As such potential changes to the design to make it more suitable for specific applications have been offered in this section.

These changes are less about actual choices in the design and more about enabling options given the constraints of the solution. One such option is friction mounting a target object which can easily be done with threads in the holes used for setting the angles in the angle plate component. This would allow a piece of metal, wood, plastic, etc., to be placed between the bolts and the target object, thus increasing the strength of the friction mount by tightening the bolts on either side.
If more options are of interest, then instead of the holes at the bottom of the target frame, replacing them with grooves would allow any combination of holes to increase the available angles vastly. For example, this would enable every $2,5°$ increment between $22,5°$ and $45°$ using only the $45°$ mounting point on one side and every other on the other side. This would move the axis of rotation from the projectile's trajectory, which means this increased flexibility could reduce the accuracy from a guaranteed shot to the center to a slightly offset target location.
If the offset that the presented target frame mounting bracket deals with is of no concern, then simply replacing it with a cylinder with holes in the same four locations as the mounting bracket would prove a more straightforward solution. This cylinder could be flattened on one side to provide a resting surface equal to the existing mounting bracket.
The current solution uses a fixed 300x300 plate size. However, this is intended only as a

placeholder to display the capacity of the solution. Other smaller frames can be mounted to the same brackets or holes in the angle plates is designed for it. The limitation of the solution with differently sized frames is set to handle any plate size that ensures no contact between the frame and projectile. If objects with geometries other than flat squares are to be tested, custom mounting solutions must be designed, e.g., based on one of the above suggestions.

6 Conclusion

The solution suggested in this project is based on the primary goal of adding additional functionality to an already functional ballistic setup. The functionality of the setup has determined the general shape of the solution. In contrast, it has been heavily modified due to the reduction in component interference which initially was a weak point of the concept. With the decision to design around an unsupported setup, as opposed to a fixed setup, designing with regards to cheap and light components becomes more reasonable. This is evident as the heaviest single component weighs only 894$[g]$ and following the suggested assembly process is the heaviest set of components, just over 2$[kg]$. The total weight of the solution without the target plates is 5.67$[kg]$. Compared to the weight of a single-threaded rod, around 3$[kg]$ is this entirely plausible for an addition to the existing setup.
With no manufactured component requiring unique material or complex manufacturing methods, the estimated costs are easily within reasonable levels. The primary point of compromise is the operability where changing angle requires loosing and tightening four nuts and bolts, which while easily doable, is potentially tedious compared to the alternatives.

The impact simulation revealed the direction the plate moves after the impact ranged from 0° to 35° relative to the trajectory of the existing setup. Meanwhile, the ball could depending on the angle, begin to move partially back towards the air cannon. This means that the absorption material, which needs to be placed around the setup to catch the ball and the plate and any sizeable fragments, needs to be spread in a large area depending on the angle used. The solution has not incorporated any means of placing this material; however, given that the solution angles the target plate upwards can some of the material be placed on top of the threaded rods without issue. The remaining coverage could be done either by hanging from the top or covering the space between the main front pillars of the existing setup.
The final verdict on whether or not the suggested solution is suitable requires testing the manufactured version in the actual setup. However due to time constraints and the ongoing corona pandemic has this not be feasible during the project. Therefore realizing the design, testing its capabilities and limitations are subject to future work and could therefore be a side project in conjunction with another smaller project. Testing the solution in this way would likely also highlight areas where improvements can be made. Generally this solution cannot be deemed perfect however it serves as a foundation on which the perfect solution could likely be made.

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A Concepts

This section of the appendix contains the alternative concepts which the solution could have been based on. They are presented in the same manor as the concept in the report with certain aspects of each concept described in its own subsection.

A.1 Manual Concept

The manual concept uses the threading on the threaded rods in order to move each corner of the target frame individually. Using the threading to change the angle gives the design a lot of flexibility at the cost of it becoming tedious to change the angle given the bottom mounting points requires two nuts each. The flexibility given by adjusting each mounting point separately allows for a surface angled to the side as well as up or down. This flexibility comes at the cost of a high load on the individual mounting points as well as a tedious mounting procedure. The manual concept can be seen from the side and in a 3D perspective on figure A.1 and A.2.

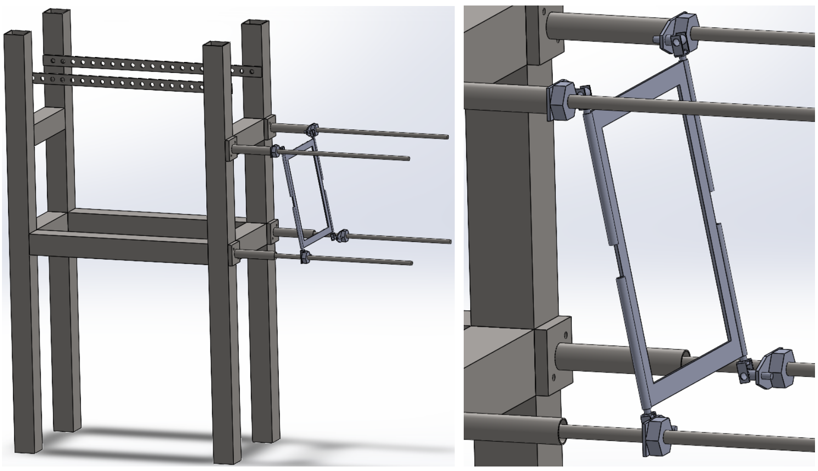

Figure A.1: 3D drawing of manual concept

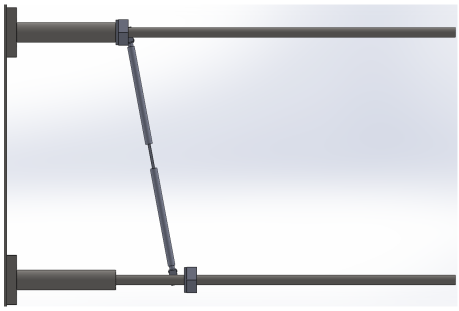

Figure A.2: Side view of manual concept

A.1.1 Sliding Mechanism

As the angle changes as does the distance between the mounting points. This means that each mounting point requires a sliding mechanism on the target frame see figure A.3. Selecting the height can then either be done by having a tighter fit that requires a large force, e.g. a hammer, to move it or by threading one of the bottom rods and tightening a nut to determine the height. The sliding mechanisms needs to sustain the loads at any extension without deforming or taking damage such that the operability is reduced. This is expected to cause problems in the long term use of the concept.

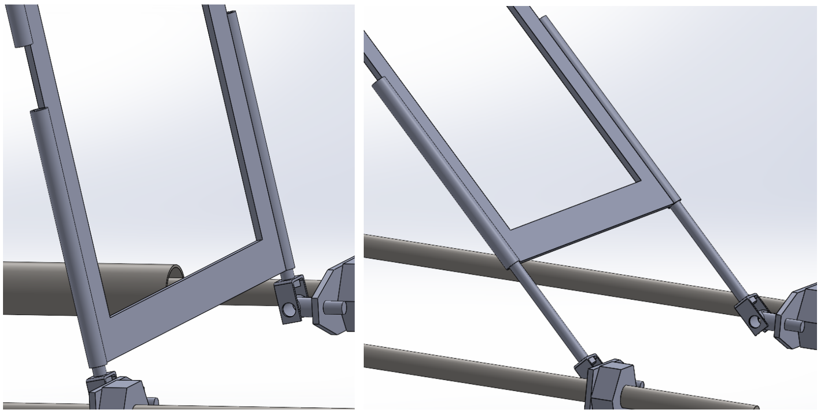

Figure A.3: Two positions of the sliding mechanism

A.1.2 Mounting Mechanism

Assuming the functionality of rotating the target frame in two directions is never used is the mounting points reduced to two types one at the top and one at the bottom. The top mounting points uses a single nut to keep the mounting plate in place up against the pipe. This is sufficient as the top mounting points never needs to move for any angle of the target frame.
The bottom mounting points requires two nuts on each threaded rod to keep the frame in place. By using nuts and a plate can any angle be chosen however since the angle is determined by moving the point out on the threaded rod will each angle specification need to be measured and the uncertainty of the angle is determined based on the measurement.

In order to allow the necessary functionality of the joints has a custom design based on existing hinge designs been adopted. The highlighted component in the design seen in figure A.4 is lacking a pin or bolt which the rods will then rotate around. The adopted bolt design going through the mounting plate is fixated using a corresponding nut. When assembling the concept can the tightening of the nuts be left until last such that the rest of the concept can fall in place allowing the sliding mechanisms to work uniformly.

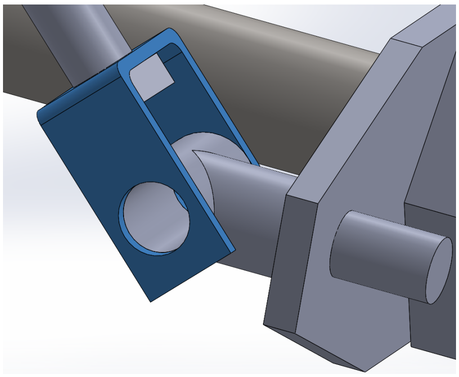

Figure A.4: Rotational joint required to accommodate the angle of the target frame

A.1.3 Target Fixture

Unlike the other concepts are there no apparent components which can deliberately fail if a unsupported target setup is preferred. This means using tape or other relatively unobtrusive means is required in such a scenario. Given the target frame is a structural component in the design will the mounting of the target plate to the target frame have to be done in the lab. If a fixed setup is desired can the target frame be used with holes for either nuts and bolts or other mounting equipment that does not heavily impact the structural rigidity of the concept.

A.2 Swing and Frame Concept

This and the subsequent swing design has the target frame mounted to a shaft such that the plate can rotate around a specific point. Rotating around a specific point allows slots to be made such that the angle which the target frame is set to is prescribed instead of manually dialing it in for every change in angle like with the manual concept. The side view and 3D perspective drawing of the concept can be seen in figure A.5 and A.6.

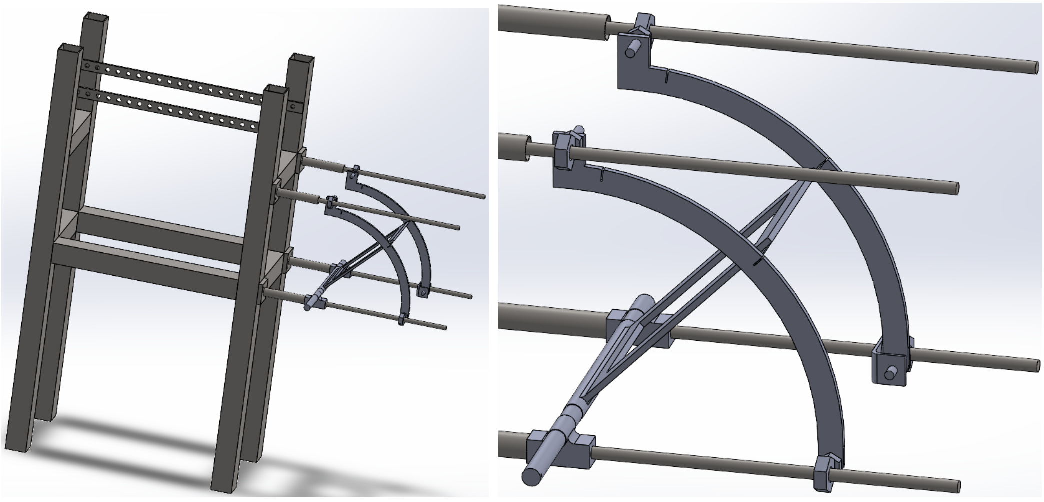

Figure A.5

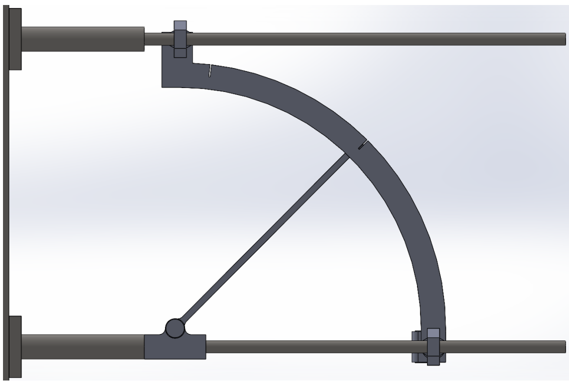

Figure A.6

A.2.1 Slotted Frame

This concept has slots directly made into two plates which are mounted separately on the threaded rods. The choosing of a specific slot is then simply made by placing a thin plate into one of the slots which the target frame then rests upon. This design means that any loads transferred to the structural frame is done so through the shaft and onto the threaded bars. Since the target frame is resting on the plate and not connected to the plate in any way are no loads transferred to slotted frame. This allows the frame to be made thinner and from lighter and cheaper components thus reducing the cost and complexity associated with the manufacturing.

The slotted frame is mounted to the threaded bars on both the top and bottom end of the frame to keep the structure steady. This means that supporting the two slotted frames are four mounting points.

A.2.2 Target Fixture

With the target frame rotating around a specific point and being free at the other end will the impact onto the target plate cause both the target frame and target plate to rotate around the shaft. It is possible to have a fixed setup where both the target plate and frame is securely mounted at the other end however this will cause the loads to propagate through the slotted frame.

A.2.3 Shaft Mounting

Mounting the shaft to the threaded bars is done through first threading two mounting brackets onto the rods at the bottom and then slotting the shaft through both of the brackets from the side. This separates the components thus reducing the weight of individual components and also making the mounting process more manageable than if the setup was connected initially. The consequence of this process is that the shaft needs to be positioned above the threaded bars instead of between them. This moves the loads from the impact away from the threaded bars thus increasing the need for support on both the shaft and the threaded rods.

A.3 Swing and String Concept

This concept uses the same swing design as the previous concept however instead of using a slotted frame mounted on the threaded bars this concept uses a string between the target frame and roller mounted at the top of the structural frame.

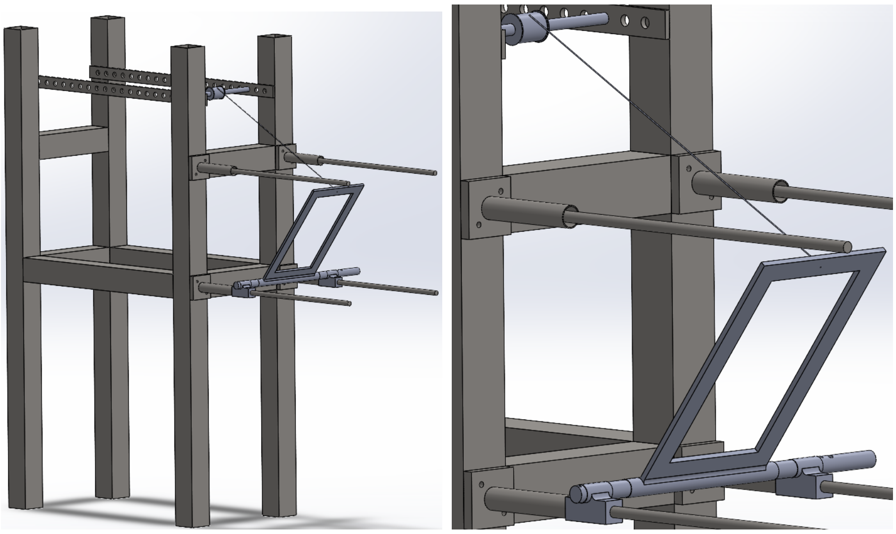

Figure A.7

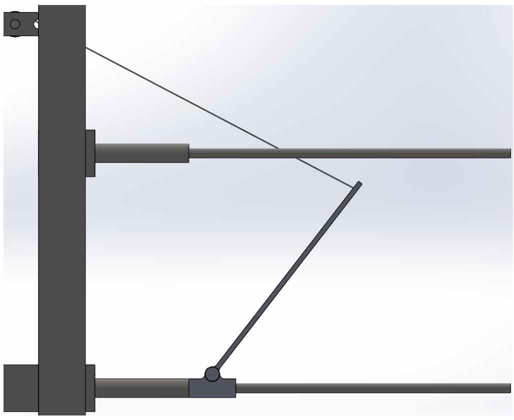

Figure A.8

A.3.1 Roller Design

The roller works by a certain degree of rotation of the roller would cause a corresponding change in rotation for the target frame. Adjusting the target frame to a specific angle could then be done in two ways either through manually measuring the desired angle and then locking the roller or through a slotted roller with prescribed angles for each slot.

A.3.2 Roller Mounting

Since the string only has to carry the weight of the target plate and frame can it be mounted anywhere without any structural concerns. In the depiction of the concept has the plates on top of the existing setup been used as a example of a mounting location and method.

A.3.3 Target Fixture

As the design uses the same swing and target frame design as the swing and frame concept does the same possibilities and limitation apply here. However creating a fixed setup would be difficult as the string would be under a heavy load and possibly have to be changed in favor of a wire. Additionally this would set requirements to the mounting location or how the wire goes from the roller to the target frame.