Impact Mechanism for Testing Lightweight Ceramic Armour Systems

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Client: ARL-MLS Lab

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The ARL-MLS lab at the University of Toronto requires a way of testing lightweight ceramic armour systems. The lab has provided the team with a salvaged machine that can be repurposed to design a new impact test rig. It is standard practice to perform high velocity or ballistic velocity impact tests on ceramic samples; however, due to limited space in the ARL-MLS lab and to ensure students' and operator's safety, this project will not be exploring ballistic or high-velocity impact tests. Instead, the scope of this project will be to design a Technology Readiness Level 4 low-velocity impact testing rig prototype that is capable of causing and measuring an impact on ceramic armour samples.

Background research indicates that there are two possible types of impact tests that this project can be based off of. Firstly, a drop weight test. In this test, a projectile of a specific mass and shape is raised vertically to a predetermined height and released such that it impacts a test sample once where the desired impact force is achieved through a single impact. Alternatively, a repeated impact test requires a steel ball to be placed on top of a sample to act as a force distributor. A hammer is then used to repeatedly impact the ball. For this capstone project, a similar setup could be followed, but only one impact would occur where the force would be equal to the force of the desired projectile impact velocity.

For this project to be declared a success, the ceramic sample must experience an impact velocity of 5m/s, and the testing rig should sense or calculate the impact force. The project should also cost no more than $500 CAD, and should rank TRL 4. The design must adhere to all safety standards and codes expected of an experiment conducted in an UofT lab and fit into the designated space given by the ARL-MLS Lab (i.e. where the existing machine stands). Beyond this design team and the ARL-MLS lab, the design needs to consider and not impact the individuals accessing the lab in any way.

This document outlines the client's problem, needs, and requirements for a successful design. Following the approval of both the ARL-MLS Lab and the supervising professor, the next steps will be to generate potential solutions and prototype the chosen design.

Table of Contents

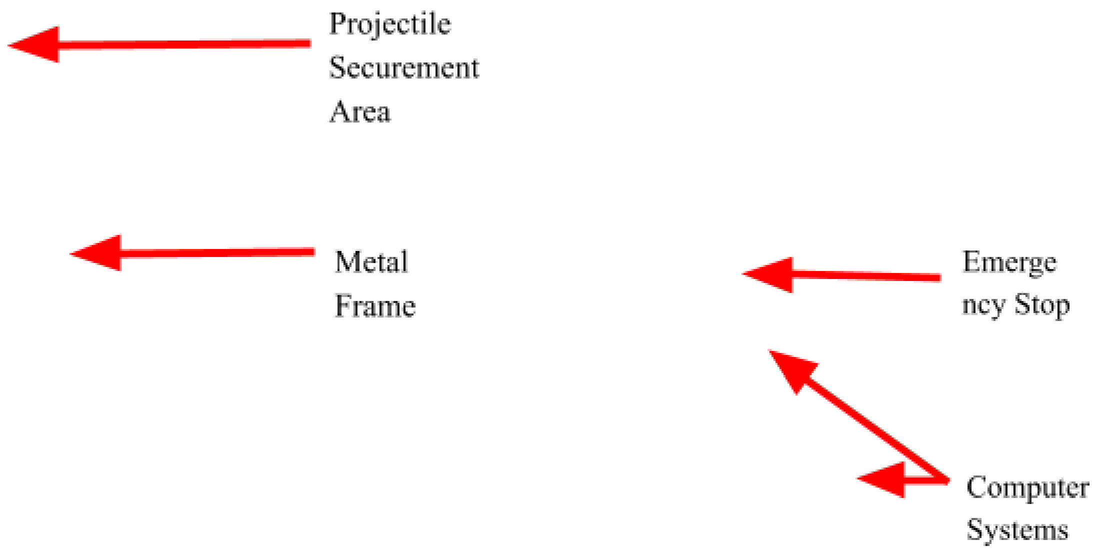
1.0 Introduction

Ceramics have been identified as a favourable material for the development of high protection, lightweight armour systems due to their low densities and high intrinsic strengths [1]. However, ceramics are brittle, which means that they are likely to fracture and crack upon impact [1].Therefore, to fully explore the potential of ceramic use in armour systems, they must be tested in a controlled environment. This can be done using an impact testing mechanism [2]. Impact can be defined as the force or action of one object hitting another [3]. There are two main categories of impact testing, namely, low-velocity testing and high-velocity testing [4]. Low-velocity testing methods include the charpy and drop weight impact tests. The high-velocity testing method is referred to as ballistic testing [4]. This document details the specific problems, the current state of the art, as well as the necessary design requirements.

2.0 Problem Statement

The ARL-MLS lab has tasked this capstone design team with repurposing pre-existing machinery, shown in Figure 1 below, into an impact testing rig for ceramic armours. The testing rig should be capable of dropping and applying a calibrated force to the projectile, as well as measuring impact velocity and calculating the impact energy.

The impact testing rig must follow all safety guidelines and other physical limitations, detailed objectives and constraints are discussed in Section 6.0. The design should consider all stakeholders, as well as its design for cost, human factors, safety, and the environment, which are discussed in Section 6.6 in further detail.



Current Setup of the Drop Test Rig in the ARL-MLS Lab

3.0 Background

This section explores state of the art drop weight testing setups by reviewing experimentation performed within the last 5 years as well as modern testing machines. Drop weight impact tests are used to simulate the expected impact a material would experience in the field [4]. Figure 2 shows the general setup of a drop weight test.

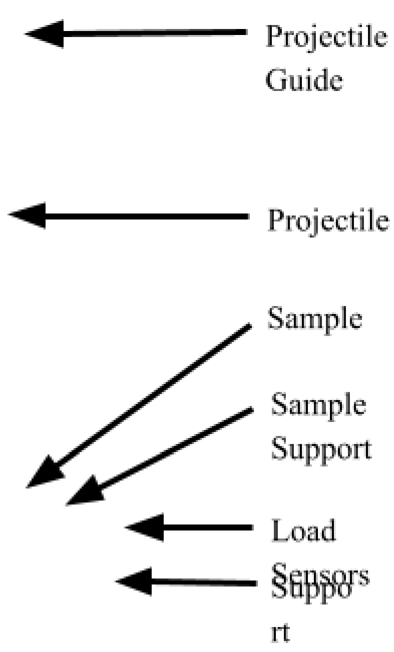


Figure 2: Setup Used to Test 3D Glass Fibre Reinforced Polymer Laminates [5]

The operation of the above test is as follows: a projectile of a specific mass and shape is raised vertically to a predetermined height, released, and impacts a test sample once [4]. The sample itself is typically flat in shape, of a set thickness, and clamped around its edges [4]. The control system involves using sensors together with high speed cameras to measure the impact force, velocity, and the sample response at the instant of impact [5].

Alternatively, rigs can also be designed for repeated impacts [6], [7]. Figure 3 shows the standard testing rig for a multi-impact drop test.

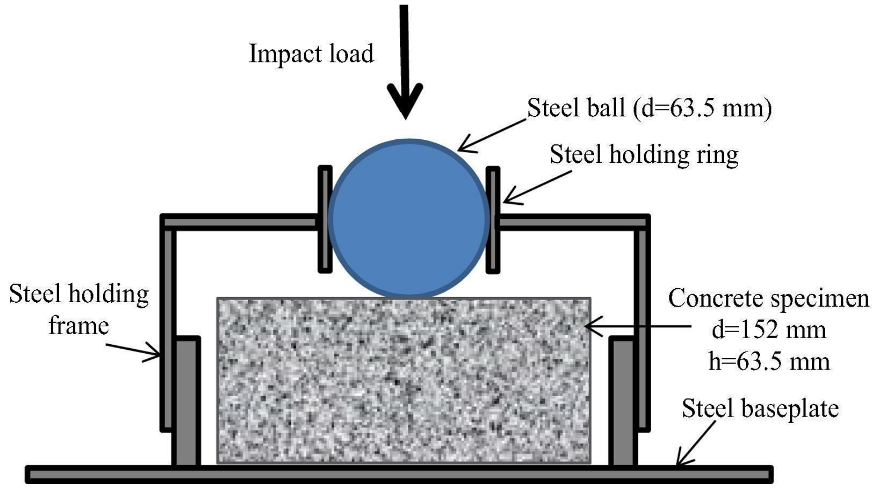


Figure 3: Lower Portion of the ACI 544-2R RBDWI Testing Rig [7]

The operation of the rig is as follows: a steel ball is placed on top of the sample to act as a force distributor and a hammer/weight is then used to repeatedly impact the ball. The number of impacts until the first crack is recorded and used to determine the material properties of the sample.

There are also standardised rigs available for purchase on the market such as the ZwickRoell DWT high-energy drop weight tester [8].

Figure 4: ZwickRoell DWT40 5m HDWT40 5m High-Energy Drop Weight Tester [9]

These machines are computerised, and allow for a wide range of drop weight testing [9].
Using the details in the above figures, the project can be broken down into the following subsystems:

- Controls and Electronics System
- Rig Framing
- Projectile System
- Test Sample

3.1 Controls and Electronic Systems

The controls and electronic subsystem encompass all aspects of the project related to the actuation of the rig, collection of data, calculation of results, and display of results. Typically, impact velocity, force, and energy are the recorded or calculated variables during the experiment.

Theoretically, impact velocity is the velocity of the projectile during its collision with the ceramic sample; experimentally, it is measured just before collision. During impact tests, impact velocities, in both cm/s and m/s ranges, are commonly measured using optical sensors [10], [11]. As seen in Figure 5 below, Kyushu University used a combination of laser diodes and photo-detector units to measure the projectile's velocity [12].

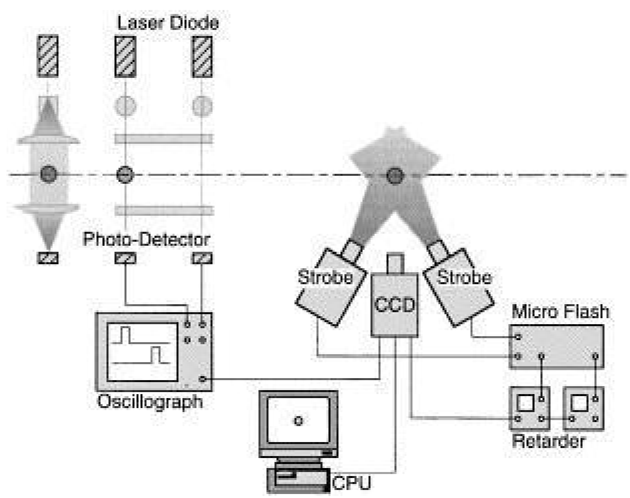


Figure 5: Kyushu University Velocity Measurement Capture System [12]

The AFWAL Materials lab used a combination of phototransistors, light emitting diodes, and 10-MHz counters to measure their impact velocity as seen in Figure 6 below [10].

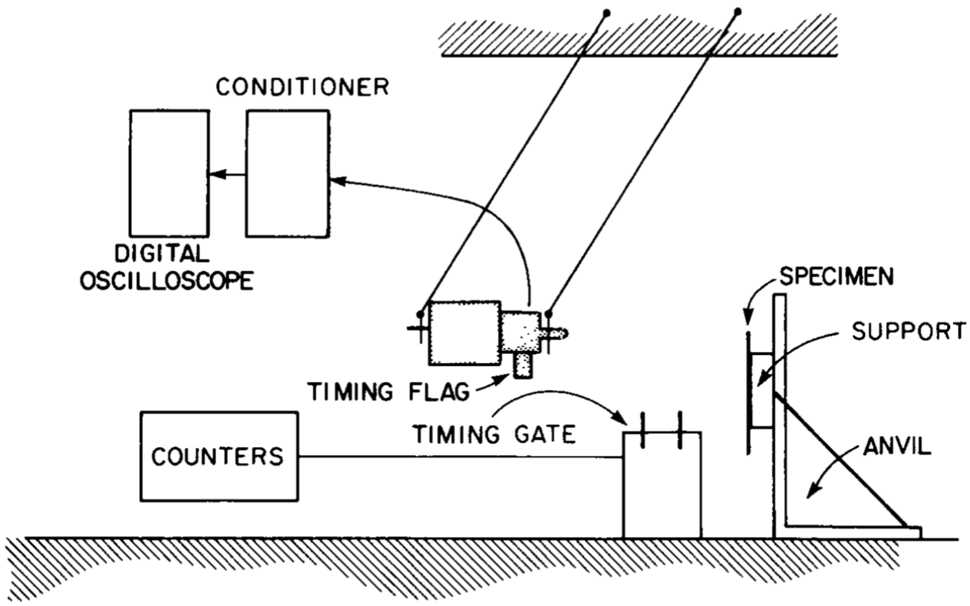


Figure 6: University of Dayton's AFWAL Materials Laboratory Impact Experiment Test Setup [10]

The impact force can be measured using force transducers, a conditioning amplifier, sound card, and MATLAB's Data Acquisition Toolbox. Figure 7 below, shows an example layout for impact force measurement [13].

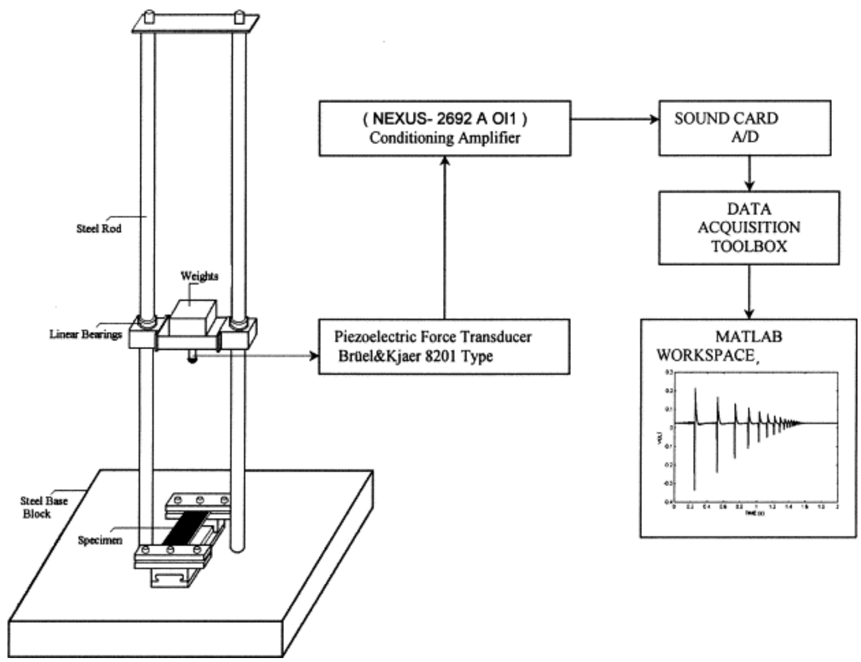


Figure 7: Low-Velocity Drop Test Impact Force Measurement Procedure [13]

As detailed in Section 4.3 below, the impact energy can be calculated through integrating under the load-displacement curve of the sample during impact. In order to generate the load-displacement, strain gauges, or load cells can be used [14].

3.2 Rig Framing

The rig framing is the physical structure of the impact mechanism. The machinery pictured in Figure 1 will be modified into the rig framing. However, the team has observed that the rig framing for a standard state-of-the-art drop test on ceramics exceeds a height of 3m, which exceeds the height of the given machinery [5], [9]. As such, the team must design a ceramic testing rig that differs from the current state-of-the-art.

Further research revealed that drop testing is widely used to test concrete samples [6], [7]. The current standard is the ACI 544-2R RBDWI test [7]. This test involves impacting a concrete sample multiple times using a rig framing that is approximately 0.5m tall. While the testing of concrete is beyond the scope of this project, the principles applied in the ACI 544-2R RBDWI can help the team modify the given machinery.

3.3 Projectile System

The projectile system involves both the projectile itself, as well as a mechanism to hold and release/fire the projectile. Generally, the projectile is spherical in shape, made of metal, and sized smaller than the sample area. For example, a sample of size 145x190mm requires a projectile of diameter 80mm [5].

The hold/release mechanism varies based on the complexity of the drop test system being used. The simplest version of this mechanism involves using a clamp to hold the projectile in place and opening the clamp to release the projectile [5]. A more complex mechanism involves using a series of pulleys to hold, release, and reset the projectile [9]. Another alternative is the use of electromagnets to hold and release the projectile [15].

3.4 Samples

As stated in the introduction, the purpose of the test rig will be to simulate the testing of a lightweight ceramic armour system. Typically, this is done by testing a fixed ceramic sample with a backing layer. Similar impact tests have used the following as samples [16]:

- Ceramic Tile Mosaic + Epoxy Resin (e.g. Alumina (Al_2O_3))
- Ceramic + Metal Backing Layer (e.g. Steel 4340)
-

This section details the equations required to calculate the impact velocity, impact force, and impact energy associated with a simple drop test. These equations will be used as a starting point for the design of the physical impact testing mechanism. Note that all calculations assume air resistance is negligible.

4.1 Impact Velocity

The impact velocity of a drop test can be found using the law of conservation of energy [17].

Potential Energy, $PE = mgh$

Kinetic Energy, $KE = \frac{1}{2}mv^2$

Law of Conservation of Energy: $PE = KE$

Thus: $mgh = \frac{1}{2}mv^2$

Solving for v gives: $v = \sqrt{2gh}$

Where:
m - mass of projectile
h - drop height
g - acceleration due to gravity
v - impact velocity

4.2 Impact Force

The calculation of impact force involves the work energy principle [17]. This principle states that the work done on a system is equal to the change in kinetic energy of the system [18].

$$W_{net} = \frac{1}{2}mv_{final}^2 - \frac{1}{2}mv_{initial}^2$$

$$F = \frac{W_{net}}{d}$$

W_{net} - net work done

m - mass of projectile

v_{final} - impact energy

$v_{initial}$ - initial velocity (0 m/s)

F - impact force

d - distance travelled after impact

Note that the distance travelled after impact is dependent on the type of collision. For a near perfectly elastic collision, the sample absorbs minimal impact energy and as such, the distance value is small [17] which results in a large impact force. For an inelastic collision, the material absorbs some of the impact energy and as such, the distance value is large [17] which results in a small impact force.

4.3 Impact Energy

The impact or failure energy can be found by integrating the bounded area under the sample's load vs displacement curve [5]. This curve can be drawn using data captured at the moment of impact. Figure 8 displays an example load vs displacement graph.

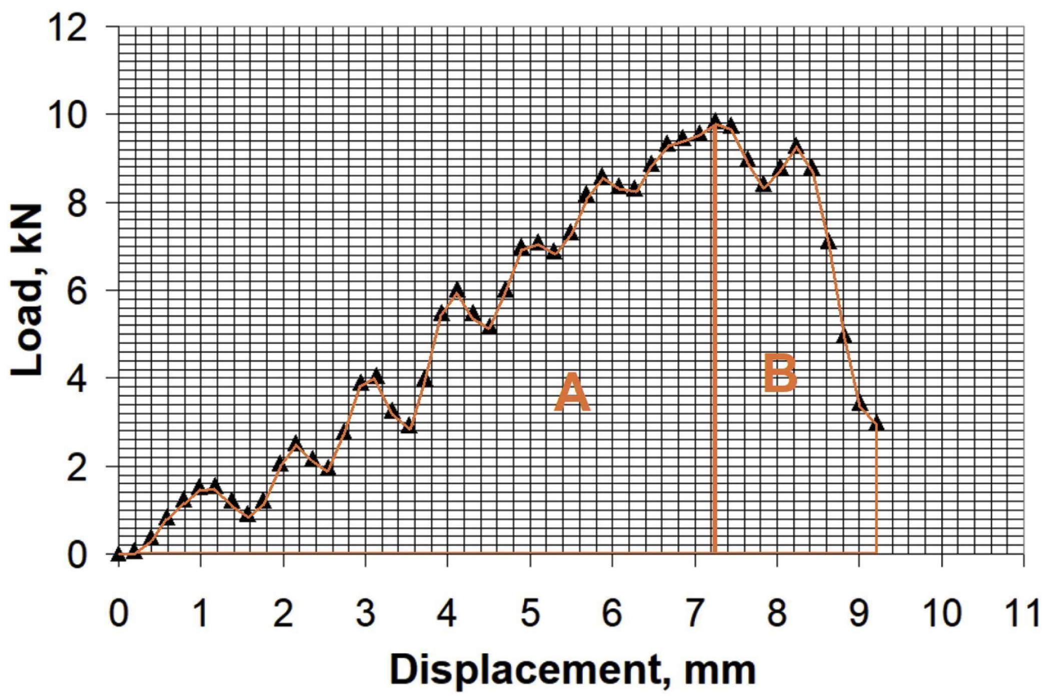


Figure 8: Load vs Displacement Example [5]

Note that the area of the graph is split into parts, A and B. A represents the energy of origin of the major failure process in the material () and B represents the energy of development of the major failure process in the material (). This split allows for the calculation of the sample's deformability index (DI). [5].

5.0 Scope of Work

Due to the size of the ARL-MLS lab and to ensure operator safety, this project will not be exploring ballistic impact tests, rather only low-velocity impact tests. Table 1 shows the scope for each subsystem based on the background research.

Table 1. Scope for Each Subsystem

<table>
<tr><th>Subsystems</th><th>Scope</th></tr>
<tr><td rowspan="2">Controls & Electrical</td><td><u>Controls:</u>
Record, calculate, and display:
Drop Height
Projectile Weight
Impact Velocity
Impact Force
Impact Energy
Calibrate applied force</td></tr>
<tr><td><u>Electrical:</u>
Electrical components required to integrate projectile and control system
Sensors required to measure results</td></tr>
<tr><td>Projectile</td><td>Releasing the projectile such that it achieves a low impact velocity</td></tr>
<tr><td>Sample</td><td>Choosing proper ceramic samples and sizing for the experiment</td></tr>
<tr><td>Rig Framing</td><td>To repurpose the existing machinery and integrate with other subsystems</td></tr>
</table>

As per the client's requirements, the system should be prototyped to a level 4 rank on the Technology Readiness Level (TRL) scale, which requires a complete proof-of-concept work that validates the successful performance of a system and achieves the project requirements [19]. An instruction manual on how to operate the test rig will be provided. In summary, the scope of this project is to design and prototype the projectile, control, and electrical systems of a low-velocity impact testing rig, that is able to cause and measure an impact on ceramic armour samples, to a TRL4 level. This project will be completed over an 8-month period with an allocated budget of $500 CAD. Therefore, while inspiration for this project can be taken from the similar experiments discussed in the background section, space and cost considerations must be made.

6.0 Detailed Requirements

This section highlights the functions, objectives, and constraints that will be considered in the design of the low-velocity drop test rig. Additionally, client-driven and industry-driven parameters such as stakeholders, cost, and safety standards are discussed.

6.1 Functions

The purpose of this project is to design a low-velocity impact testing rig that is capable of testing ceramic samples to assist in ceramic armour research. The primary and secondary functions of the final design outline the actions the test rig will perform, and they are listed below.

Primary Functions:

1. Holds the projectile in a secure starting position
2. Applies a predetermined, calibrated force to the projectile during the launch sequence to achieve a projectile target velocity
3. Launches the projectile vertically to impact the unit under test (UUT)
4. Contains the projectile within the testing rig set-up
5. Produces repeatable and reliable test results

Secondary Functions:

1. Records the maximum velocity of the projectile
2. Records the impact velocity of the projectile
3. Calculates the absorbed energy of the UUT
4. Calculates the strength of the UUT

6.2 Objectives

The low-velocity impact testing rig should abide by client driven and technology driven parameters. Table 2 states the goals for the technology, along with a metric and the reasoning/testing method for each objective. Further justification and calculations behind the reasoning for each objective can be found in Appendix A. The objectives are ranked in order of importance through analysing the project's requirements and client's goals for the design. The vital objectives have their target level highlighted. The goals and levelling systems were determined through researching the current state of the art and understanding the client's expectations.

Table 2. Impact Testing Rig Objectives, Metrics, and Reasonings

#	Objective	Objective Levels		Reasoning/Testing Method
1	Projectile should attain low velocities	L1	Less than 1m/s maximum	Reasoning: High-velocity testing is unsafe for U of T students [20]. A slower speed of 10m/s was suggested by the client for safety purposes. Testing method: Velocity can be determined by dividing height over measured time.
		L2	Between 1-5m/s maximum	
		L3	Between 5-10m/s maximum	
		L4	Between 10-20m/s maximum	
		L5	Over 20m/s maximum	
2	Design should hold projectiles of various masses and sizes securely	L1	Holds masses of less than 50g	Reasoning: Projectiles of different masses and sizes should be held firmly in place by the design before testing begins [21]. Testing method: Test the machine by holding projectiles of various masses until failure.
		L2	Holds masses between 50-100g	
		L3	Holds masses between 100-150g	
		L4	Holds masses of 150g or greater	

3	Design should apply a force to the projectile to attain low velocity	L1	Applies up to 0.004N to the projectile to achieve velocities of less than 1m/s	Reasoning: The design will require a mechanism that launches the projectile to impact the unit under test with a low velocity. Testing method: Where acceleration can be found using accelerometers or projectile velocity.
		L2	Applies 0.004-0.1N to the projectile to achieve velocities of 1-5m/s	
		L3	Applies between 0.1-0.4N to the projectile to achieve velocities of 5-10m/s	
		L4	Applies between 0.4-1.6N to the projectile to achieve velocities of 10-20m/s	
		L5	Applies over 1.6N to the projectile to achieve velocities over 20m/s	
4	Design should contain the UUT and projectile within a constrained boundary	L1	Design does not contain the UUT and projectile within the testing set-up	Reasoning: Containing the projectile and any fragments from the impacted unit under test within a certain boundary is critical for operator safety [22]. Testing method: Achieved if an impact test occurs without the projectile or any UUT fragments escaping the containment area.
		L2	Design contains the UUT and projectile within 700x720x570mm (WxDxH)	

		L3	Design contains the UUT and projectile within 490x450x565mm (WxDxH)	
		L4	Design contains the UUT and projectile within 250x150x145mm (WxDxH)	
5	Design should rank Technology Readiness Level 4	L1	TRL 1	Reasoning: The client has requested TRL 4 for the design, which requires prototyping and a final functional product [23]. Testing method: Achieved once a prototype has been built and the design has attained all the other objectives.
		L2	TRL 2	
		L3	TRL 3	
		L4	TRL 4	
		L5	TRL 5+	
6	Design should be affordable	L1	Costs more than $500 to prototype	Reasoning: The design should not be too expensive, as there is a $500 budget given by UofT. Testing method: A complete bill of materials will be kept for the final design with the total calculated cost.
		L2	Costs between $250-$500 to prototype	
		L3	Costs between $100-$250 to prototype	
		L4	Costs less than $100 to prototype	

7	Design should produce multiple impact tests	L1	Design can produce 3 impact tests or less	Reasoning: Successive testing will be required to test the strength of different types of ceramic armour in response to impacts from different projectiles [24]. Testing method: The number of successful impact tests (objectives 1 and 3 are achieved each time) will be counted. Achieved if the machine does not fail or break between/during tests.
		L2	Design can produce between 5-10 impact tests	
		L3	Design can produce between 10-20 impact tests	
		L4	Design can produce more than 20 impact tests	
8	Test set-up and duration should be short	L1	Test set-up and duration takes over 20 minutes	Reasoning: The test duration should be kept short to maximise time efficiency and data collection. Testing method: Measure the time duration from setting up the system to when the impact test result displayed. The level will depend on the duration of this interval [24].
		L2	Test set-up and duration takes between 10-20 minutes	
		L3	Test set-up and duration takes between 2-10 minutes	
		L4	Test set-up and duration takes under 2 minutes	

6.3 Final Design Objectives

Table 3 outlines the level the final design will attain for the objectives that are most relevant to the scope of this project. Appendix A Table A2 outlines the reasoning for selecting and levelling these objectives in further detail. These objectives and their levels were selected based on the clients expectations, scope, feasibility, and timeline for this design project. .

Table 3. Final Design Objectives and Target Levels

Objective	Target Level	Reasoning
1	L2	The client has stated that 5m/s (L2) would be a safe objective.
3	L2	To achieve speeds of 5m/s, forces between 0.004-0.1N (L2) are required.
4	L2	Current technology that achieves velocities of 5m/s for impact testing use this size containment area for testing and safety, indicating that L2 should be attained [22].
5	L4	The client requires the project to achieve TRL 4 unless safety is compromised.
6	L2	As the team does not plan on using personal funds for the project, a L2 objective is justified.

6.4 Constraints

The client has established various constraints which are conducive to creating an adequate final design. Furthermore, the team has identified additional constraints related to safety and machine precision. The constraints for the design can be found in Table 4 below. For further justification and information, Appendix B provides a detailed reasoning behind each objective.

Table 4. Impact Testing Rig Constraints and Essential Goals

#	Constraint	Reasoning
1	Must drop the specimen from 1.8m-2.5m.	The client has specified a drop height of 1.8m to 2.5m maximum for the testing rig, as it will be required to fit inside the ARL-MRS lab.
2	Must abide by ISO 45001 safety standards [25].	ISO 45001 outlines the standards for basic safety procedures [25].
3	Differences in calibration of the projectile velocity, UUT weight, and impact energy before and after the test, must be less than 7%.	To ensure consistent test results, the impact test rig must remain calibrated during testing. The guideline for impact testing is that calibrations for the projectile velocity, UUT weight, and impact energy taken before the impact test must be no more than 7% from calibrations taken after the test [24].
4	The projectile must be launched vertically, and accurately impact the unit under test.	The test performed must be a vertical drop test where the projectile accurately impacts the UUT with enough force to test its strength and absorbed energy.

6.5 Stakeholders

The following tables show the internal and external stakeholders, which are individuals or groups of people who are impacted by the design either directly or indirectly.

Table 5. External Stakeholders

Stakeholders	Impact
Client - ARL-MLS Laboratory	The design should fit the client's need to test ceramic armour.
Operators	The design should ensure the safety of the individual operating the machine.
Individuals accessing the building/lab	The design should not affect or cause potential harm to the students or professors accessing the building/ lab.
University of Toronto	As the design will be implemented in the Mechanical Engineering Building, UofT holds a certain degree of liability if individuals or buildings were to be impacted.

Table 6. Internal Stakeholders

Stakeholders	Impact
MIE491 Capstone Design Team	The design should be safe to assemble and test to ensure safety of the design team.

6.6 Design for Excellence (Dfx)

This section considers other aspects of the design such as cost, assembly, human factors, and safety. Dfx considerations for manufacturing and environment can be found in Appendix C.

6.6.1 Design for Cost

When sourcing for parts, a cost analysis should be performed to minimise cost. Table 7, breaks down how each subsystem can be designed to minimise cost.

Table 7. Subsystem Design to Minimise Cost

Subsystem	Considerations
Controls & Electronic System	Repurpose electronic components on the pre-existing machinery
	Source for affordable electronic components (e.g. Digi-Key or Amazon)
	Utilise coding software licences provided by UofT
Frame	Provided by the ARL-MLS lab
Projectile System	Repurpose components on the pre-existing machinery
	Source for affordable mechanical parts (e.g. McMaster-Carr)
	Utilise the free UofT Engineering workspaces (e.g. MakerSpace)
Sample	A cost analysis should be run on the three possible samples used for impact tests [16].

6.6.4 Design for Human Factors

The main use case of this design will be for the member of the capstone team operating the rig, while the secondary use case will be for the member of the ARL-MLS Lab operating it.

Table 8. Subsystem Design for Human Factors

Subsystem	Considerations
Controls & Electronic System	A knowledge of programming should not be required to operate the system
	All results and parameters should be clearly displayed
Frame	The user must be able to identify the frame and its components
Projectile System	The area where the projectile is placed must be identifiable
	The area where the sample is placed must be identifiable
	Samples should be labelled for clarity
	Instructions on how to operate the rig will be posted on the side of the rig
Sample	A physical and electronic manual will be given to the lab manager of the ALR-MLS lab

The following table shows the general guidelines for each sub system to ensure a safe design.

Table 9. Subsystem Design for Safety

Subsystem	Considerations

Controls & Electronic System	Emergency stop system should be in place
	The system should confirm that the testing area is clear before operation
	All electronic components should be properly sealed and grounded following the MIE UG Health and Safety Standard [26]
Frame	Testing area should be clearly marked
Projectile System	A physical barrier should be in place to bar anyone from entering the testing area
	The force generating mechanism should be physically impossible to access.
	The holding mechanism should be accessible only before the test starts
Sample	During testing, the sample needs to be secured such that contact with the projectile will not cause it to escape the testing area
Overall Design	All safety features should be colour coded in red for ease of visibility and to impart a sense of urgency.
	Non-flammable and non-conductive materials should be used when possible to lower the risk of fire
	During testing, the ISO 45001 standard for safety, which outlines the requirements for an occupational health and safety management system, must be followed [25]

6.7 Service Environment

The drop test rig will be operating in the ARL-MLS laboratory therefore, the rig and its method of operation must adhere to all MIE UG Health and Safety Standards [26]. The design must not disturb any ongoing tests in the lab. The environmental conditions of the impact test should be kept at 22˚C, and humidity should also be regulated to ensure no changes to a specimen's physical properties [24].

7.0 Conclusion

In conclusion, this project aims to design and prototype a low-velocity impact testing rig, that is able to cause and measure an impact on ceramic armour samples, to a TRL 4 level over the span of 8 months. This will be achieved by utilising the equipment and space provided by the ARL-MLS lab and Uoft Engineering. A full resource table can be found in Appendix D.

To ensure the success of this project, below is a breakdown of the key management milestones and deliverables. A Gantt Chart and Contribution Table can be found in Appendix D.

Design Review — Jan 13 2023

- Research on each subsystems
- Team internal review/presentation on researched material
- Final decision on design for each subsystem
- DR summary and presentation

Poster and One pager — Mar 24 2023

- Prototype design

Capstone Design Showcase — Apr 05 2023

Pending approval from the client and supervising professor, the team will begin the design iteration process.

8.0 References

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9.0 Appendices

Appendix A - Objectives

Table A1. Detailed Objective Reasoning Descriptions

#	Objective	Reasoning
1	Projectile should attain low velocities	Some high-velocity impact test rigs can achieve speeds of up to 200m/s [20], however these are dangerously high speeds that could result in injuring the University of Toronto students using the testing rig in the future. As students are more inexperienced with this machinery, a slower speed of 10m/s was suggested by the client for safety purposes.
2	Design should hold projectiles of various masses and sizes securely	Modern bullets such as the 150-grain round nose, can weigh up to 10g [21]. If the bullet is held at one end and the tip is vertically facing downwards, a normal force of at least 0.0981N (F=0.01*9.81) should be applied to the other end to hold the bullet securely in the machine.
3	Design should apply a force to the projectile to attain low velocity	Assuming a projectile of 10g as in objective number 2 and a drop height of maximum 2.5m as per the client constraints, one can find the required force () to achieve the desired projectile final velocities.
4	Design should contain the UUT and projectile within a constrained boundary	By investigating other drop impact testing machines, we can gather the test area dimensions of machines that can launch the projectile between 0.77-4.65m/s. As these speeds are within the team's objectives, similar test containment areas should be used for this design [22]. Containing the projectile and unit under test within a certain boundary is critical for operator safety.

5	Design should rank Technology Readiness Level 4	TRL level 4 requires that the basic components of the system be integrated together to establish proper mechanical function [23]. The client has requested prototyping and a final functional product, thus a TRL level 4 was assigned as the project objective by the client.
6	Design should be affordable	The University of Toronto MIE491 capstone course has provided a budget of up to $500 for capstone projects. The team can go beyond this limit, but the university will not fund the additional expenses.
7	Design should produce multiple impact tests	Constraint number 3 outlines the calibration requirements for the design. Design repeatability will be closely related to differences in calibration. The design should achieve the same impact velocity and impact area (within plus or minus 7% [24]) when calibrated correctly. A design that can achieve successive testing will ensure more reliable results, which are critical when using the results to test the strength of different types of ceramic armour.
8	Test set-up and duration should be short	When transferring the specimen from its pre-conditioning environment to the drop test rig, the conditions might differ, in which case the test-set up and duration must occur quickly enough to ensure consistent physical properties [24]. Impact should occur at most 2 minutes after the sample has been removed from a conditioning environment [24].

Table A2. Detailed Final Design Objectives Reasoning

Objective	**Target Level**	**Reasoning**
1	L2	The client has stated that velocities above 10m/s are dangerous for the team to attain, and that 5m/s (L2) would be a safer objective. This test should attain low velocities to meet the client's requirements.
3	L2	To achieve speeds of 5m/s, forces between 0.004-0.1N (level 2) are required. As the client expects speeds of 5m/s, this objective was selected for further design development.
4	L2	Current state-of-the-art achieving velocities of 5m/s for impact testing use this size containment area for testing, indicating that level 2 should be attained [22]. This objective relates to safety, which is crucial when designing an impact test, explaining why this objective was selected.
5	L4	The client requires the project to achieve TRL 4 unless safety is compromised. This objective was selected due to the emphasis the client has put on attaining a TRL 4 project.
6	L2	As the team does not plan on using personal funds for the project, a level 2 objective is justified. This objective was selected as cost will be a limiting factor when deciding the final design.

Appendix B - Constraints

Table B1. Detailed Constraint Reasoning Descriptions

#	Constraint	Reasoning
1	Must drop the specimen from 1.8m-2.5m.	The current test rig that can be found in the ARL-MRS lab is around 2 metres tall. If this machinery is repurposed for this project, the constraint of a drop height of 1.8m-2.5m will be attained. Otherwise, the client has specified a drop height of 1.8m-2.5m for this capstone project. The drop test rig will be required to fit inside the ARL-MRS lab for University of Toronto research purposes, further justifying a maximum height of 2.5m.
2	Must abide by ISO 45001 safety standards [25].	ISO 45001 outlines the occupational healthy and safety standards by the International Organisation for Standardisation [25]. These standards include basic safety procedures to reduce workplace risk and create safe working conditions. As University of Toronto students will be using this equipment in the future, it is important that the machinery abides by legal safety standards.
3	Differences when calibrating the projectile velocity, UUT weight, and impact energy before and after the test, must be less than 7%.	The International Systems of Unit (SI) are the physical units based on the metre, kilogram, second, ampere, kelvin, candela, and mole used to measure the design impact energy, projectile velocity, and unit weight. To ensure consistent test results, the impact test rig must remain calibrated during testing. The guideline for impact testing is that calibrations of any form of SI units taken before the impact test must be no more than plus or minus 7% from the calibrations taken after the test [24]. Elsewise,

		the test must be performed again, as the machine was not properly calibrated and the test results are inaccurate.
4	The projectile must be launched vertically, and accurately impact the unit under test.	The launching mechanism of the design should provide enough power to the projectile for it to travel at low velocities when it is launched from a specific height. This velocity should be high enough such that the projectile successfully impacts the unit under test with enough force.

Appendix C - Design for Excellence

Design for Environment

The project is limited geographically to the ARL-MLS Laboratory. The main effect on the environment would come from the energy consumption required to build the rig and the materials used and purchased to create the design. Table C1 outlines the potential effect on the environment for each subsystem.

Table C1. Subsystems Potential Effect on the Environment

Subsystem	Considerations
Controls and Electronic System	The energy consumption of operating the rig should be minimised by minimising the time it takes to to initialise and perform the test and calculate and display the results
Frame	The frame will be repurposed from the existing structure in the ARL-MLS lab thus negating the need for additional materials to be consumed
Projectile System	The energy required to create the materials is outside this team's control
	In order to minimise energy consumption, the time and energy required for the chosen manufacturing process should be considered
	The energy required to create the materials is outside this team's control
Overall Design	When possible, when sourcing materials, one shipment order should be placed to reduce the unnecessary energy consumption associated with shipping in parts

Design for Manufacturing and Assembly

As the project is scoped to creating a TRL-4 prototype, it is not necessary to consider the manufacturing and assembly processes for the market.

Appendix D - Project Management

Table D.1. Team Contribution Table

Team Member	Tasks
Nathalie Cristofaro	• Revising problem statement and introduction • Functions, objectives, and constraints sections • Final design objectives section • Full document final revision
Jasmine Chen	• Problem statement (scope) • Design for Excellence • Stakeholder • Gantt Chart • Revising Introduction • Conclusion
Kevon Seechan	• Revising problem statement and introduction • Background • Equations
Victoria Velikonja	• Executive Summary • Background (Controls and Electronic Section, Samples Section) • Design for Excellence • Service Environment • References • General Editing and Formatting


2023
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Current Month
Design Review
Sensor for Recording Impact Velocity - research
Calculation for Absorbed Energy - research
Stress and Strain on Frame Structure - research
Internal Presentation of Researched Material
Calibration System - research
Release Mechanism - research
Apply Force on Projectile Mechanism - research
Precision Control - research
Work on DR Summary and Presentation
Prototyping
Poster
One-Pager
Capstone Design Showcase Prep
Problem Requirement
Problem Statement

Table D2. Resource Allocation Table

Resource	Explanation
Rig Frame	The frame for the rig has been provided by the client, the ARL-MLS Lab
Lab Space	Our client, the ARL-MLS Lab have granted us access to their space to work and repurpose the frame
Complete DeWalt Mechanical Toolbox	Any tools needed to repurpose the frame have been provided by the client, the ARL-MLS Lab
$500 CAD	The University of Engineering office will reimburse the team up to $500 CAD for any resources needed for this project
University of Toronto Mechanical Engineering Machine Shop	As everyone on the team has undergone the George Brown Basic Machining training and are full time Mechanical Engineering students, access to the machine shop is permitted and covered by the Mechanical Engineering Chair's Office.
University of Toronto Makerspace	As University of Toronto Engineering student's, access is permitted to UofT's Makerspace, with resources such as 3D printing are available