Development of a Mechanical Shock Test Equipment

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Development of a Mechanical Shock Test Equipment

Pre-testing products to ensure sufficient structural strength before certification shock tests

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Abstract

A simpler version of a shock-testing machine was developed and built. This allows engineers at Verisure to test prototypes and early versions of new products before the product is certified. An independent company shock tests the product as part of the process to certify it as an approved home alarm security product.

During the shock test, the product is subjected to a high acceleration during a short time (pulse). The shock shall be a half-sine, 100 g, 6 ms pulse, in accordance with the certification standards [1], [2]. A commercial shock-testing machine was not a suitable option and a simpler version, specifically suited for this case was therefore needed. This report details the steps taken as part of the development process leading up to the construction and testing of the shock-testing equipment.

The design choices made throughout relies mainly on physical testing instead of complex FEM simulations in the effort of reaching the end goal of building the test equipment within the thesis' limited time. The final design is a Free Fall Drop Tower type design with the frame comprised of aluminum profiles and steel rods with linear bearings to guide the motion of the carriage on which the product is mounted. The half-sine pulse shape is generated when the carriage impacts the polyurethane cylinder, called the "programmer", at the bottom and is measured by an accelerometer mounted on the carriage.

All target specifications were met, and the shock testing equipment can produce the needed shock pulse to an acceptable level.

Keywords: Mechanical shock, Shock testing, Half-sine curve,
Product development, Shock-testing equipment

Sammanfattning

En enklare version av en chocktestmaskin utvecklades och byggdes. Detta möjliggör att ingenjörer på Verisure kan testa prototyper och tidiga versioner av nya produkter innan produkten certifieras. Ett oberoende företag chocktestar produkten som en del av processen för att certifiera den som en godkänd hemlarmprodukt.

Under chocktestet utsätts produkten för en hög acceleration under en kort tid (puls). Chocken skall vara en halv-sinus, 100 g, 6 ms puls, i enlighet med certifierings-standarderna [1], [2]. En kommersiell chocktestmaskin var inte ett lämpligt alternativ i detta fall och en enklare version, som var anpassad för dessa omständigheterna behövdes därför. Denna rapport beskriver de steg som togs inom den produktutvecklingsprocessen som leder fram till byggandet och testningen av den slutliga chocktestsutrustningen.

De designval som gjordes förlitar sig i huvudsak på fysiska tester istället för komplexa FEM-simuleringar i ett försök att nå slutmålet av att bygga testutrustningen inom examensarbetets begränsade tid. Den slutliga designen är en design av typen Free Fall Drop Tower där ramen bestående av aluminiumprofiler och med stålstänger och linjärlager för att styra slädens rörelse där produkten är monterad. Halv-sinuspulsen genereras när släden träffar polyuretancylindern, kallad "programmer", och mäts med en "data logger"-typ av accelerometer monterad på släden.

Alla målspecifikationer uppfylldes och chocktestutrustningen kan producera den nödvändiga chockpulsen tillräckligt för att uppnå en acceptabel nivå.

Nyckelord: Mekanisk chock, Chocktestning, Halv-sinuskurva, Produktutveckling, Chocktestsutrustning

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Lund, October 2019

Ola Månsson

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1 Introduction

This master thesis was made at R&D Hardware department at Verisure Innovation AB during the period March 2019 to September 2019. The purpose of this thesis was to design a shock-testing equipment suitable for the small-scale testing needed at Verisure.

1.1 Background

For Verisures alarm system to be classified as an approved home alarm system according to the Swedish and European standard, all products included in this alarm system must meet certain requirements governed by the alarm system standard SS-EN 50131 [3]. One of these tests is a shock test where the product is subjected to a number of shock pulses designed to test the product's *"immunity to mechanical shocks, which are likely to occur, in the service environment"* [1]. In this shock test, the product is subjected to a very high acceleration during a very short time, i.e. a shock pulse. The criteria which determine whether the product passes the shock test vary slightly depending on the type of product. But in essence, the product should endure the shock pulses without breaking.

These shock tests are performed by an independent certification company. The products are generally tested after the products' first production run. If the product doesn't pass the shock test, it then needs to be altered, manufactured and tested once more. The companies performing these tests are often fully booked several weeks or months in advance. Thereby, not passing a certification shock test the first time can have a significant impact on both the project's cost and schedule.

It would therefore be desirable for Verisure to have their own equipment to perform these type of shock tests before hand. Prototypes could thereby be tested throughout the design phase, potentially finding weak points early on and thus insuring that the product will pass its certification shock test.

1.2 Establishing the Problem

Several shock-testing machines are available to purchase, but they are expensive and are more complex than what is needed for Verisure. Most shock-testing machines are made to handle products of a wide range weight and size and have the ability to produce shock pulses with several types of shapes and wide range of pulse duration. To accommodate all this and having a high accuracy and repeatability, the machines are large, bulky and heavy, often weighing several hundred kg. They are generally made to be used for high volume testing, thereby meant to be used a lot, and often include systems allowing for automated shock testing since some test criteria require several consecutive shocks.

In contrary, the shock testing needed at Verisure are in many instances the opposite. The shock testing is only needed for a few occasions per year and the product weights are relatively low, rarely more than 0.5 kg. Furthermore, the shock pulse specifications are very specific and the amounts of shock tests per product are low so there is no need for any automated testing. As Verisure doesn’t have a large machine shop to permanently place one of these shock-testing machines in, it’s also desirable to have a machine, or test equipment, with a lower weight and size and preferably one which is moveable, thus it can be stored somewhere else when not in use.

In short, the available machines are generally much to complex, bulky and expensive for the small-scale shock testing needed at Verisure.

1.3 The Goal

The overall goal was to design a simpler version of a commercial shock-testing machine. A shock-testing equipment which have a reasonable low cost, which is easy to manufacture, intuitive to use and which is moveable when not in use. Though it must still have be sufficient accuracy and consistency thus a reliable prediction can be made whether the tested product is likely to pass its certification shock test.

The end goal was to produce a 3D model of this shock-testing equipment and to verify the validity of the proposed design through concept testing and calculations. A suitable way of measuring these shock tests should also be found, as well as an easy way to post-process the test data. The design and its parts should be in such a state that they were ready to be manufactured, if Verisure then wanted to continue with the project.

Depending on how quickly the work progressed, the plan was to also include the building of a full-scale prototype of the test equipment. The goal was that this prototype, if performing sufficiently well, would then be the finished product.

However, the design should be made such that it could easily be modified and refined at a later date, if needed. The decision whether to include this part as well was planned to be taken after the pre-study and initial concept tests were done and in agreement with the project's supervisors at Verisure and LTH. The end-goal was intentionally left this vague as it was difficult to estimate what could reasonably be achieved in this time frame, as this subject was outside of Verisures normal area of expertise.

1.4 Delimitation

This work was limited to 20 weeks of work for one student. The end product should be a complete 3D model of the test equipment, or possibly a full-scale prototype. As much as possible of the parts needed for concept testing and the prototype were to be manufactured by external companies to reduce the work load.

The work should also include a report where the test method, the test equipment's functions and the underlaying calculations and reasoning are explained so that the work of building and optimizing the test equipment could be continued by Verisure at a later date.

If more complex calculations or FEM simulations were needed, then these were also to be outsourced to an external company with this type of expertise.

1.5 General shock-testing terminology

This chapter contains a brief explanation of how the shock pulse is defined and some of the more common shock-testing terminology used throughout this report.

The purpose for using this type of standardized shock test is to *''reveal mechanical weakness and/or degradation in specified performances, or accumulated damage or degradation caused by shocks"* as described in the shock-testing standard IEC-60068-2-27. There are several standardized shapes (or shock profiles) which the pulse can have. In this case the shock profile is a half-sine curve as defined by the Home Alarm certification standard [1]. Although it's in practice unlikely that a product is subjected to a shock with this shape, in such a pure form, the use of a pulse shape like this *"provides a reproducible method of simulating the effects of more realistic shocks"* [1].

1.5.1 **Shock profile**

The shock profile is the acceleration curve representing the variation in acceleration that the product experiences during the short time period of the shock. The parameters used to define this shock pulse are the shape of the pulse, the peak acceleration and the pulse duration. In this case the shape is a half-sine pulse. The peak acceleration is generally measured in g's or m/s^2 and the pulse duration is measured in milliseconds (ms). Figure 1.1 shows a half-sine shock curve where $\hat{A}$ is the peak acceleration and the pulse duration $D = t_D - t_0$.

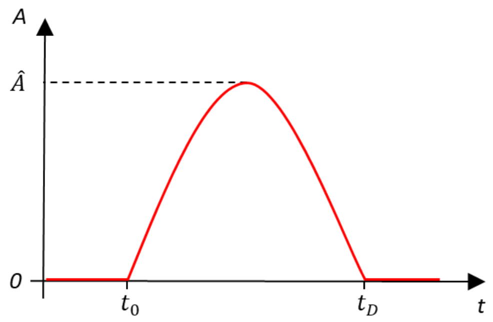

Figure 1.1 A half-sine shock pulse

1.5.2 **Main components of a shock-testing machine**

Almost all shock-testing machines produce the shock pulse using the same principle. A carriage, on which the product is mounted, is given a velocity before it impacts a "programmer" which abruptly changes the velocity and direction of the carriage. It's this rapid change in velocity which creates the intended acceleration curve.

The programmer dimension and characteristics is what determines the overall shape of the shock pulse. The peak acceleration and duration of the shock is then governed by the carriage's impact velocity and the weight of the carriage in combination with the programmer's characteristics.

Figure 1.2 shows a generic model of a Free Fall Drop Tower type of shock-testing machine. Although the look, placement and function of these components might differ somewhat, all impact shock machines, regardless whether it’s a Free Fall Drop Tower design, a Pendulum design etc., have the same fundamental functions.

The product being tested (the DUT) is mounted on a fixture which allow it to be mounted in different orientations as it’s required that the product is tested in different orientations. The fixture is in turn mounted to a table (or carriage). The carriage can move along two guide rods which ensure that the shock, and the motion of the carriage, is only applied along one axis. In this example the carriage is given a velocity before impacting the programmer at the bottom by dropping the carriage from a given height. Although the velocity could also be generated in other ways. The programmer is mounted to a heavy reaction mass (or impact block) which is suspended on some type of dampener. The reactions mass helps absorb the energy of the impact and isolates the programmer from the fixed support or frame of the machine.

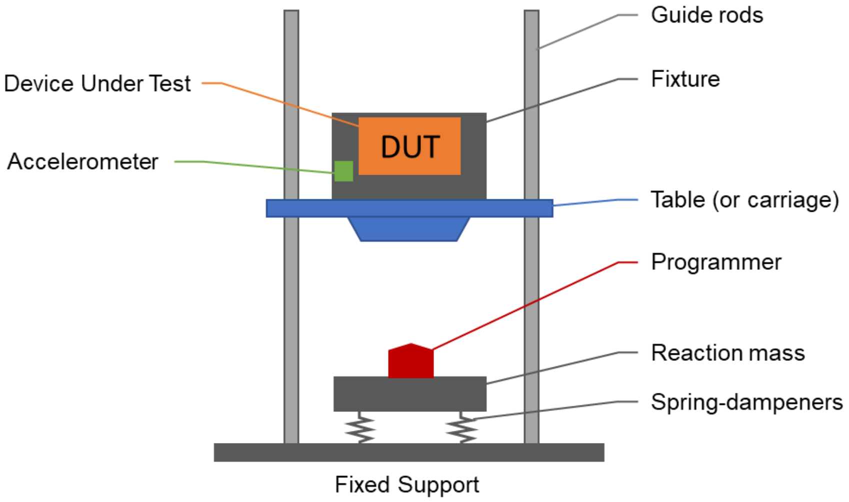

Figure 1.2 Main components of a generic Free Fall Drop Tower type shock-testing machine.

2 Method

This chapter describes the different steps taken in development process used to develop the shock-testing equipment. The method was based on the "generic product development process" described in Ulrich and Eppinger [4], but adapted to better suit the given circumstances and the end goal.

The step-by-step process described by Ulrich and Eppinger [4] in its entirety describes the product development process for a mass-produced product. The product in this case is a custom design, for one customer and with a narrow range of test parameters. Thereby, the relevant part of this generic development process was mainly in the concept development phase.

The product being developed is referred to as a shock-testing equipment, or the STE, due to the intention of making a simpler version of the automated shock-testing machines normally used.

The project was divided into three phases. An overview of the different steps in these phases are shown in Figure 2.1 and Figure 2.2.

The first phase was a sort of pre-study. This included an initial research of the shock testing procedure, the certification standard and the design rules and guide lines for shock-testing machines. Then to establish the customer needs and the target specification for the STE. An evaluation of the different shock-testing machines available on the market was also done. This was in part done to get a better understanding of the general functionality and to identify areas which potentially could become problematic or difficult in this project. It was also done to gather ideas and inspiration. The aim was never to design a test equipment which where radically different from any existing shock-testing machines. Since the timeframe for developing this STE was relatively short, the decision was made to focus on using methods and designs which had been used on other machines and was therefore proven to work. The challenge was instead to find a way to implement this and create a simple, low-cost design, which produced sufficiently consistent shock tests and within given tolerances.

As equipment used for measuring the shock pulse, i.e. an accelerometer, would be needed during the concept testing phase as well, and due to long delivery times, an accelerometer had to be bought before the concept development started. Researching the shock measurement equipment and procedure as well as purchasing the accelerometer were therefore done as part of this first phase. The plan was for this accelerometer to then be used as part of the final STE as well.

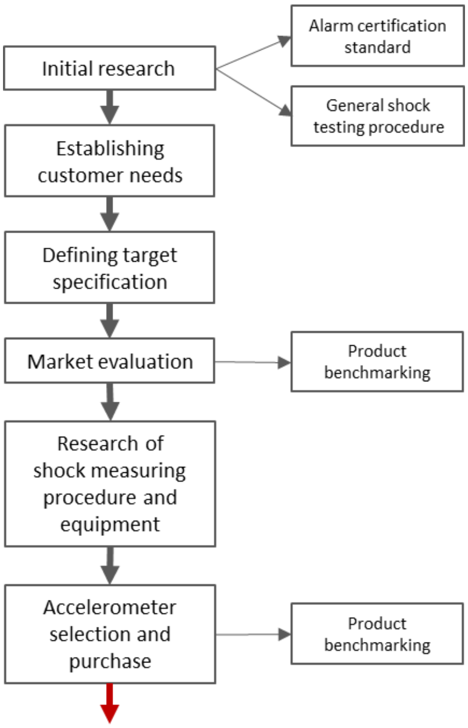

Figure 2.1, First phase of the product development process.

The second phase of the product development process was to design the STE. This included the iterative process of concept generation and concept testing as well as concept selection, as described by Ulrich and Eppinger [4]. Some more basic structural calculations of the forces involved was also included to dimension the STE after. However, any more complex FEM calculations were to be avoided, if possible, to save time. A complete CAD model of the final concept was then to be made.

The third and last phase was to construct a full-scale prototype which if all went well could become the final product as well. Thereby this phase first included finding companies to manufacture the custom parts. The assembly was then to be made at Verisure. Lastly, some initial testing and calibration was planned. However, if any further modifications and upgrades where needed to achieve the necessary performance, then that work would be handed over to Verisure's employees. Figure 2.2 shows the steps involved in phase 2 and 3.

The project plan and the development method were from the beginning expected to change as the project progressed and the understanding of the subject became better. This also included what end result could reasonable be achieved within the time frame, as explained in previous chapter.

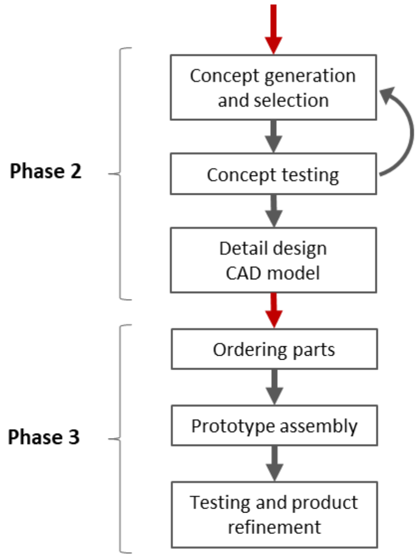

Figure 2.2, Phase 2 and 3 of the product development process.

3 Customer Requirements

This part describes the customer needs and the shock testing requirements set by the international alarm system standard. The target specification for the STE is then defined based on these standards.

3.1 Customer Needs

The customer needs are the demands and wishes of the customer for how the STE should function and be developed. The customer, in this case, is Verisure Innovation AB. The customer needs were acquired through several discussion with employees from the Mechanics team at Verisure. These employees were also the intended users of the STE. The needs were then compiled into several main points and divided into two groups, primary and secondary needs, based on their relative importance. The needs can be seen in the list below.

These needs are described in quite general terms, and it was deliberately avoided not to include any specific solutions if not necessary. The needs were later on interpreted into more clear and measurable specifications in Chapter 3.3.

Hereinafter, the product being tested in this STE will in accordance with the terminology used in the shock-testing standard IEC 60068-2-27 [2] be referred to as the “specimen”.

Primary needs

- The shock profile produced by the shock tester must either be within tolerances set for a certification shock test, or it must be sufficiently close so that the result is comparable to the real shock test.
- The shock profile must be equal over time so comparisons between tests can be made. The shock profile should not be different if the same specimen is tested at two different times with the same input variables.
- The shock profile must stay consistent independently of the weight of the specimen.
- It must be possible to accommodate all products within Verisure’s current and coming portfolio. Both relative to weight and physical dimensions.

- It must be possible to mount the specimen in all orientations needed in the shock testing standard.
- The shock pulse amplitude (g-force) must be adjustable in the range of 50-150 g.
- It must be safe to use the shock tester.

Secondary needs

- It should be easy to use the shock tester since different persons with varying prior knowledge of shock testing are expected to use it.
- There should be a way to verify the applied shock pulse. I.e. using an accelerometer, or similar equipment.
- It should be moveable, so it can be stored away when not in use. Some disassembly is acceptable to achieve this.
- It should have a simple and robust design. Thereby it should be insensitive to normal handling and usage.
- It should require minimal maintenance. It should “just work” after being stored for a long time.
- It should not require a reinforced floor. The shock tester should be constructed so that the forces transferred to the floor are kept to a safe level. Thereby to avoid the risk of damaging the floor and the building caused by the high impact events.
- It should work using no more than a standard wall outlet as a power source. Thereby, it should not require pressurized air, a hydraulic system or similar.
- It should be reasonably inexpensive compared to commercially available shock-testing systems.

3.2 Requirements Governed by the Alarm System Standards

This part is a summary of the relevant information from the testing standards SS-EN 50130-5 [1] and IEC 60068-2-27 [2], which governs how the shock test should be performed and parameters which define the shock severity.

The parameters determining if a specimen passes the shock test are set by each part of the SS-EN 50131 standard [3]. This standard defines the specifications for each different type of alarm product, e.g. a central unit, a motion sensor, etc.

3.2.1 Environmental test methods, SS-EN 50130-5

The SS-EN 50130-5 governs the different environmental testing methods used to approve an Alarm system product. One of these tests is the shock test.

The specimen tested shall be operational during the shock test. Thereby it should be turned on during the test and function as normal afterwards.

The shock pulse shape used is a *“half-sine curve”*. The exact shape of the curve is determined by the peak acceleration and the pulse duration. The shock severity, i.e. the peak acceleration (or g-force), is proportional to the weight of the specimen in order to *“limit the energy imparted to heavier specimens”* [1]. Table 3.1 shows the test parameters defining the pulse shape and severity for all alarm products.

Table 3.1, Shock pulse parameters

Pulse type	Half sine wave	
Pulse duration (D)	6 ms	
Peak acceleration $\hat{A}$ *where m is the specimen mass*	$m \leq 4.75$ kg $m \geq 4.75$ kg	Equation (3.1) No shock test
Number of shock directions	6	*(“Both directions (±), in each of three mutually perpendicular axes.”)*
Number of shock pulses per direction	3	

Equation (3.1) below is used to calculate the peak amplitude based on the products weight.

$$\hat{A} = 1000 - (200 * m) \quad (3.1)$$

For test severity expressed in G-force, the shock test standard is simplicity using a rounded off value of the earth gravity constant of $g_n = 10\ m/s^2$ as it varies slightly with altitude and geographical location [2]. Thereby

$$G = \hat{A} / g_n \quad (3.2)$$

The exact shock test procedure is not described in this standard, but it instead refers it to the IEC 60068-2-27 standard.

3.2.2 Test Ea and guidance: Shock, IEC 60068-2-27

This standard provides a standard procedure for shock testing.

The nominal half-sine curve used is shown in Figure 3.1. The length of the curve is defined by the pulse duration (D) and the maximum allowed deviation from this nominal curve is ±20% in amplitude, as shown by the solid lines in Figure 3.1.

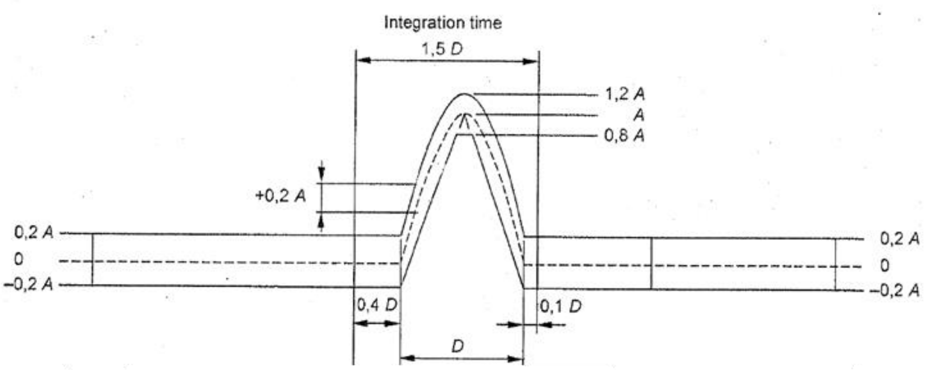

Figure 3.1, Pulse shape and limits of tolerance for half-sine curve. [2]
Dotted line = nominal pulse. Solid line = limits of tolerance. A = peak acceleration. D = pulse duration of nominal pulse.

Furthermore, the prescribed number of shocks shall be applied successively. However, the repetition rate of the shocks must be such that between shocks, the relative motion within the specimen is “substantially zero”.

One specimen is tested in all 6 directions, thereby the order in which the directions are tested can influence the result and will have to be considered for every product tested. Special circumstances can change this requirement.

The cross-axis motion must be kept below 30% of the nominal peak acceleration in the intended shock direction.

The velocity change (Δv), thereby the difference between the carriage's velocity as it impacts and then rebounds and leaves the programmer shall not deviate more than ±15 % from the nominal curve. The velocity change can be calculated by integrating the acceleration curve and the Δv is therefore equal to the area under the acceleration curve. When calculating this Δv, the integration of the acceleration curve shall be done for the time period as shown in Figure 3.1. This is in addition to the ±20% amplitude limit as stated before. A depiction of the 6 ms nominal curve in this case with the stated tolerance limits are shown in Figure 3.2.

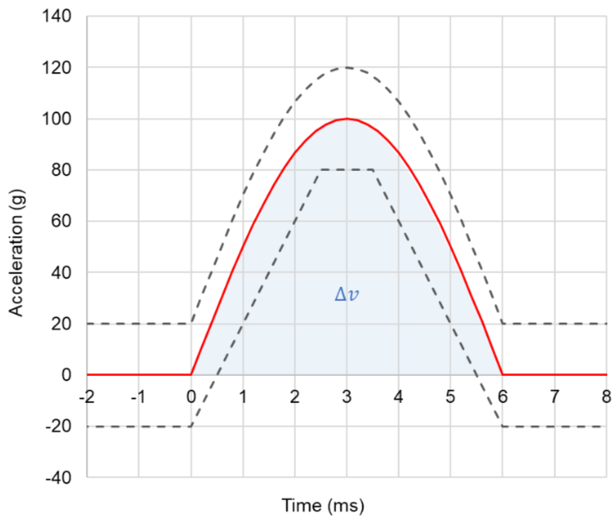

Figure 3.2 The nominal (6 ms, 100 g) pulse curve.

The specimen shall be mounted on the shock tester in accordance with IEC 60068-2-47 and the accelerometer shall be mounted as close as possible to mounting points of the product to ensure an accurate measurement of what acceleration the product is actually subjected to.

If the measuring system, i.e. accelerometer, is using a low-pass filter, then *"the characteristics of the filter should be such that its cut-off frequency (-3dB point) is not lower than 250Hz"*, [2] when using a pulse duration of 6 ms.

3.3 Establishing Target Specifications

The products target specifications are based on the customer needs and were given two values each, one Ideal and one Acceptable. The acceptable value is the bare minimum which the shock tester must be able to achieve, and the Ideal value is the preferred specification. It was given two values as it was difficult to estimate what could reasonable be achieved and as there was no previous experience from similar work at Verisure. No relevant information from similar projects, reports or products, which could be used as a guide when defining the specifications, could be found either.

Ideally the STE would be able to produce a shock pulse that were within the tolerances set by the certification standard. Thereby the shock pulse would be equally good as when testing with a commercial shock-testing machine. Ideally it would also be possible to vary the g-load to any predefined values as well as produce the same pulse regardless of the weight of the tested product. But what the lower limit, which was still acceptable, was difficult to set and had to be arbitrarily defined. However, the more important part in this case is that the shock pulses are relatively consistent so that is possible to get reliable results when testing different versions of the same product to see if the changes to the design had any effect.

The specifications were defined together with employees on Verisures Mechanics team and based on several sources. Sources such as the shock test standard IEC 60068-2-27 [4], test results from previous shock tests done on Verisure products, current and planned Verisure products, specification from commercial machines, and lastly through discussion and logical reasoning. Not all the needs were possible to quantify into a clearly defined value, and an individual assessment will in those cases be done when appropriate.

The specifications for the STE itself and for the accelerometer are shown in separate tables. Specifications for the STE itself are shown in Table 3.2 and Table 3.3. Specifications for the accelerometer are shown in Table 3.4.

Table 3.2, Target specification for the shock tester. Variables based on the primary needs.

Primary needs		*Ideal*	*Acceptable*
1.	**Produce a half-sine pulse** Aim is to be within the tolerances set for a certification test. Thereby ±20% in amplitude of the nominal pulse curve, see Figure 3.1.	±20%	±30%
2.	**Velocity change deviation from nominal pulse** Aim to be within certification tolerances	±15%	±25%
3.	**Cross-axis motion and secondary impacts** Aim to be within certification tolerances from cross-axis motion. Secondary impacts, after the carriage rebounds, should be avoided, otherwise kept below given limits.	±30%	±40%
4.	**Repeatability** Desired maximum amplitude deviation between pulse curves for tests with the same specimen. Arbitrarily chosen value. Deviation between 3 consecutive tests.	±5%	±10%
5.	**Adjustable pulse amplitude (g-force)** A larger range than necessary to include an arbitrary safety margin to the certification test and to have the ability to test to destruction.	40-140 g (5 g/step for 80-110 g otherwise 10 g/step)	90-110 g (10 g/step)
6.	**Main amplitude step (g-force)** The amplitude values that must be selectable. This corresponds to the most relevant test amplitude(s), including the certification test upper tolerance.	85, 90, 95, 100, 110 g	90, 100 g
7.	**Weight of the specimens it can test** This value is based on the weights of Verisures current product portfolio and a few relevant external products. See Appendix A.	≤2 kg	≤1 kg
8.	**Maximum dimension of the specimens tested** (LxWxH) These values are based on the dimensions of Verisures current product portfolio and a few relevant external products. See Appendix A.	-	Specimen 240x170x150 mm
9.	**Specimen mounting orientation** Possible mounting direction of the specimens. Relative to its normal mounting orientation.		All 6 directions. ±X, ±Y, ±Z
10.	**Mounting hole configuration** Fixed hole configurations or semi/fully adjustable solution to accommodate any hole configuration.	Nonspecific. Fully adjustable.	Grid structured holes
11.	**Safe to use.** The risk of bodily harm should be very low.		Risk assessment

Table 3.3, Target specification for the shock tester. Variables based on the secondary needs.

Secondary needs		*Ideal*	*Acceptable*
12.	**Easy to use.** Assessment needed. HW team at Verisure should easily understand it.	Plug & play. Intuitive functionality	Written instructions needed.
13.	**Moveable. Can be stored elsewhere when not in use.** Some disassemble can be included to achieve this.	Can be carried in small parts.	Wheeled or with a trolley
14.	**Max. weight, Total**	20 kg	100 kg
15.	**Max. weight, of each part when carried**	5 kg	20 kg
16.	**Max. weight, of each part when wheeled** Wheeled using a trolley.	15 kg	50 kg
17.	**Max. dimensions, Operational** (LxWxH)	0.5x0.5x1 m	1x1x2 m
18.	**Max. dimensions, Stored** (LxWxH) The width is based on a standard doorframe.	0.5x0.5x0.5 m	1x0.7x1.5 m
19.	**Minimal maintenance.** No calibration before each test. It should just work after being stored for a long time.	None	Reasonable assessment with HW team
20.	**Power source**	None	Standard wall outlet.
21.	**Overall cost** Not including the measuring equipment.	≤20.000 SEK	≤40.000 SEK

Table 3.4 shows an initial list of target specification for the shock tester's measurement equipment, i.e. an accelerometer. This is based mainly on the customer needs. This list was later on expanded into a more detailed list of specifications as this subject was researched in more depth as part of finding a suitable accelerometer to purchase. This is shown in Chapter 5.

Table 3.4, Target specification for accelerometer.

Accelerometer spec.		*Ideal*	*Acceptable*
1.	**Dynamic Range** The ± maximum amplitude it can measure	500 g	200 g
2.	**Max. dimensions** (LxWxH)	25x25x10 mm	100x100x50 mm
3.	**Max. weight**	50 gram	500 gram
4.	**Easy to use.** Assessment needed. HW team at Verisure should easily understand it.	Plug & play. Intuitive. No instructions needed.	Written instructions needed when using it.
5.	**Data acquisition method**	Direct connection to PC. USB or wireless.	Amplifier and separate accelerometer unit
6.	**Cost of the accelerometer** Including software.	≤10.000 SEK	≤20.000 SEK

4 Market Evaluation

A wide range of commercial shock testing machines were evaluated, to get a better understanding of how most shock testers function and what makes them unsuitable for Verisure needs. Furthermore, it provides ideas on how to solve different problems of the shock testing procedure. The method used to compare the machines is based on the "Competitor benchmarking" approach as described by Eppinger and Steven [4].

Approximately 15 shock-testing machines where compared and evaluated. These machines were the ones which met Verisures test requirements or almost met them, and some which had interesting features or way of testing. The shock pulse needed is defined by its half-sine curve shape, its peak acceleration and the pulse duration. The full list of machines is listed in Appendix B.

The types of shock-testing machines used for this type of shock testing can be divided into 4 different types. The "Free Fall Drop Tower" type is the most common. Here the specimen is bolted to a table/carriage and dropped onto a "programmer" which provides the decelerating of the carriage in the shape of a half sine curve. The carriage is guided by some sort of guide rods so that the forces only exist along one axis.

The other three type are a Pneumatic Shock Machine, an Electro Dynamic (ED) Shaker and a Pendulum type shock machine.

In a Pneumatic Shock-testing Machine, a single pneumatic cylinder provides the movement. The cylinder is positioned under the table. The table is raised and then accelerate down again using compressed air. The table hits the impact surface, i.e. the "programmer", which produces the required half-sine pulse.

The ED Shaker basically functions like a massive speaker where the input signals duration and amplitude define the movement of the table. This type is highly variable in its movement and simple to use but complex and expensive to construct.

The Pendulum Shock Machine is the least common type. A pendulum hammer is fixed at one end to an axle around which it can rotate. It's dropped from a predefined height and impacts a programmer at the bottom of the pendulum arc. The specimen can either be mounted on the tip of the hammer or on the other side of the impact block at the bottom.

No shock-testing machine was found which met all of Verisures requirements. The best alternative where the SD-10 from L.A.B. Equipment, see Figure 4.1. Although it can produce the required pulse and can accommodate the Verisure's specimen range, it's too large and is not moveable as it weighs 430 kg. Thereby it requires a permanent placement. It also costs approximately 450.000 SEK. It can produce a wide range of shocks with varying shape and size. To accomplish this, the machine is over 2m high which thereby increases the maximum impact velocity the carriage can get and is thereby able to expose the products to higher g-loads. It also has a large impact block suspended on springs at the bottom, see Figure 4.2. This to absorb the impact and protect the floor. This is mainly needed when testing heavier products and at higher g-loads. It's this impact block where most of the machines weight resides since it needs to absorb the carriage's momentum and then transfer it to the floor over a longer pulse duration, thereby reducing the peak load on the floor. Like most other machines, it also has a motor to pull up the table and an automatic release system to allow tests which requires large amount of repeated shocks to be automated.

Figure 4.1, The SD-10 shock-testing machine from L.A.B. Equipment [9].

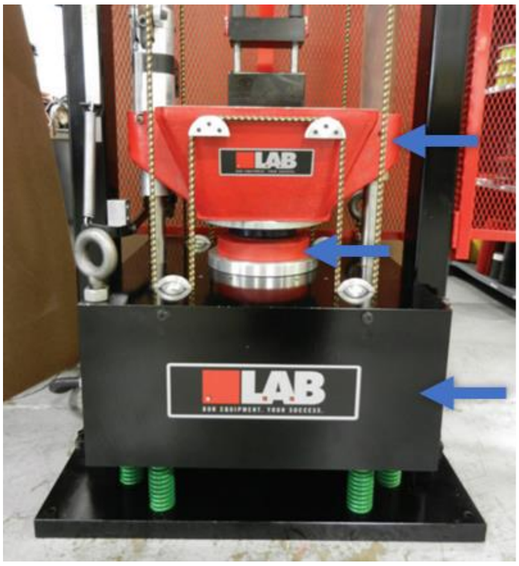

Figure 4.2, The carriage, the programmer and the impact block of the SD-10 shock-testing machine from L.A.B. Equipment [9].

Consequently, the SD-10 is more complex and expensive than what is suitable. Most machines of this type are this large, or even larger, and are designed to be placed in a real workshop. Many also require an air supply or a hydraulic system to function, which is not a suitable option for Verisure.

Two other interesting machines, which have a smaller form factor than a typical drop tower design and that can be placed on a table, is the pendulum shock-testing machine PST-300 from Shinyei and the pneumatic shock-testing machine STM5 from Elstar, as can be seen in Figure 4.3 Figure 4.4.

Figure 4.3, The PST-300. A pendulum type shock tester from Shinyei [10].

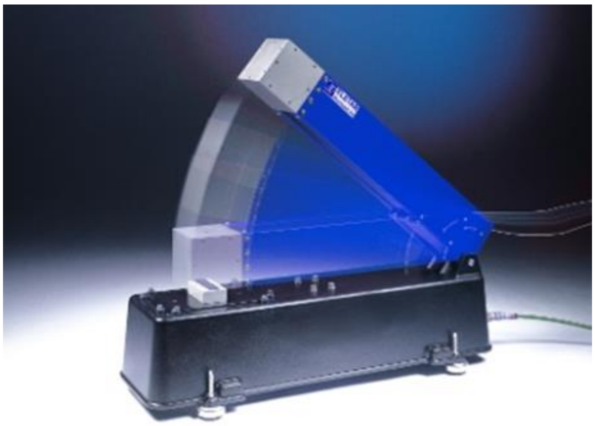

Figure 4.4, The STM5. A pneumatic shock-testing machine from Elstar [11].

These smaller alternatives which can be placed on a table is not as common. They are mainly designed to test smaller electronic components and other smaller products. Their size enables testing to be done outside of a large workshop as they can be placed on a sturdy table. However, they are still quite heavy, 100-120 kg, to be able to handle the impacts of from each shock test.

They are however not suitable for Verisure as the payload's maximum dimensions is too small. The mounting surface on the pendulum machine has a diameter of only 10 0mm and the maximum weight is also too low, 800 gram, which should include both the specimen and the mounting fixture.

But the advantages of a pendulum design are evident. The impact velocity is achieved within a smaller form factor, only using gravity and the mass of the machine is a lot lower than for the Free Fall Drop Tower machines.

On the pneumatic shock-tester the specimen is mounted onto the outside of the grey cube and compressed air is used to lift and then accelerate the arm which then impacts the programmer on the base. This design is a novel and compact solution for a shock-testing machine, however, it needs a pressurized air supply which is not viable in this case, and the mounting surfaces is again too small, only 150x150 mm.

Both machines also cost close to half a million SEK, not including an air compressor. Further details are available in Appendix B.

4.1 Fixtures

The specimen is mounted to a fixture when performing the shock test. The fixture is then itself mounted to the table. It's this fixture which allow the specimen to be fastened in the 6 different directions in which the alarm standard [1] requires the specimen to be tested in.

The fixtures used on other machines were found to be of two general designs. Either using a thick metal plate which is held vertically by struts on the backside or using a metal cube on which the specimen can be mounted, both on the sides and the top surface. An example of the first design can be seen in Figure 4.5. When mounting the specimen upside down (-Z direction), a plate is generally held up in space by spacers, or some similar feature. See the second image in Figure 4.5.

It's important that the fixture doesn't twist or bend when the shock pulse is applied as it would change the movement of the specimen and how the forces are applied to it. The general solution to this seems to be to just make all parts of the fixture out of very thick metal. This however work well when the machine is made to handle a heavy payload.

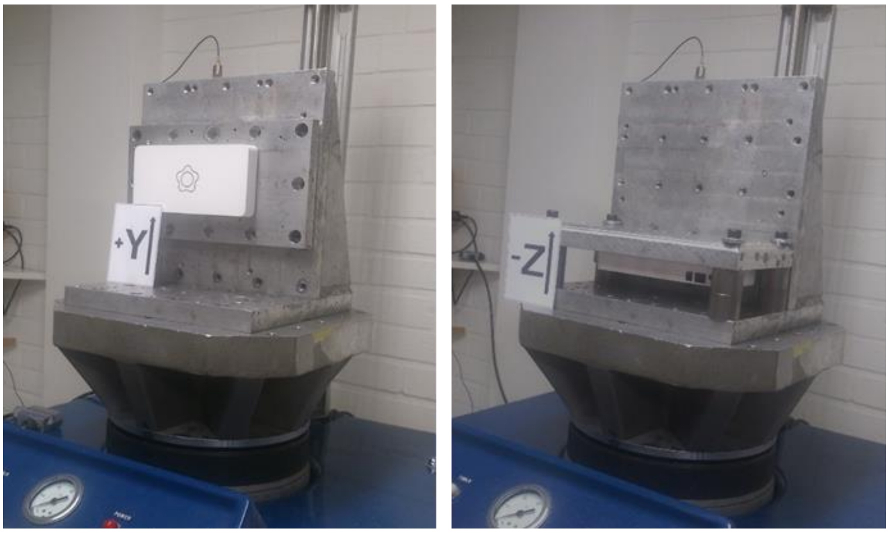

Figure 4.5 Fixture with a vertical plate. Testing the specimen in direction +Y and -Z. Image taken from a previous certification shock test.

4.2 Conclusion of the Market Evaluation

The main conclusion from this is that the less complex and lightweight type of shock-testing machine which Versiure needs does not seem to exist commercially. All available machines are made for high quantity testing, with high precision, they are made to cover a wide range of shock pulses and through automated testing. Thereby the price of the machines, where a quotation was received, were all between 400.000 – 600.000 SEK.

Most machine functions basically the same way. The Free Fall Drop Tower design is by far the most common design for this type of shock testing and for this size and weight of the specimens. The second most common is the pneumatic machines where the cylinder sits under the table and lifts it straight up.

Most drop towers are higher than 2m to achieve sufficient velocity for the higher g-loads. Much higher than what is needed in this project. Elastic bands can be added to some machines to further accelerate the carriage before impact.

Almost all machines are very heavy and require a permanent place in a workshop. Many require pressurized air or a hydraulic pump to function. All have an electric motor or pneumatic system to raise the table.

In all machines, except for the ED shakers, the half-sine curve is achieved through an impact with a “programmer”, an example of this can be seen in Figure 4.2.

Several programmers of varied dimension and material properties are provided for each machine for it to be able to produce the whole range of shock pulses. The programmers are changed depending on the pulse parameters needed. The programmer together with the impact velocity and the payloads weight define the peak g-load and pulse duration. The programmers used to produce pulses of the type and shape which is needed this for project seem all be made of the same type of material and have a similar shape. The programmers seem generally to be made of polyurethane. But it has been difficult to ascertain the exact material and dimensions used as these are rarely specified by the manufacturer. However, it corresponds well with the general description given of how programmers are designed by Lalanne in Mechanical shock and vibration volume II [5].

Almost all machines have a type of "impact block" which is a large solid mass, where the programmer is mounted on, and which the carriage impacts. This mass is there to absorb the kinetic energy from the impact and then transfers this force to the floor over a longer time duration through a set of rubber or pneumatic dampers or set of springs. Thereby minimizing the peak forces transferred to the floor, and according to several machine description, avoid the need for a reinforced floor. However, a suspended impact surface like this will inevitably affect the pulse shape somewhat. This is caused due to the impact block having time to move a little before the carriage has bounced and is no longer in contact with the programmer.

The tables (or carriages) for the drop tower and pneumatic machines are generally made to be very stiff. This is done so that the natural resonance frequency of the table won't risk interfering with the test result. Thereby the natural frequency is significantly higher than the frequency which is of interest, i.e. the pulse duration. However, a stiff and heavy table also results in that the weight of the impact block needs to be higher so that it can handle the impact from a heavier table.

5 Choice of Accelerometer

An important part of any shock-testing setup is the equipment used to measure the shock, i.e. an accelerometer. The accelerometer is used to determine what forces the specimen was actually subjected to during each test. It's from this data that a ruling can be made whether or not, the shock which the specimen was subjected to during the test was acceptable according to the certification standard.

An accelerometer was needed as a part of the final product, but also during the concept testing phase to be able to empirically evaluate different concepts. The target specifications, choice of accelerometer and reasoning behind it are briefly described in this chapter.

The most basic need in this case was that the accelerometer could measure the 100 g, 6 ms pulse with sufficient detail. The performance should also be adequate to measure a wider range of pulses, so it could be used during the concept testing phase and when debugging the STE where the pulse characteristics might differ significantly from the nominal curve.

The accelerometer is normally placed as close as possible to the specimens mounting points on the fixture. This is done to get the most accurate measurement possible to what acceleration the specimen is actually subjected to [2]. Its placement will therefore change depending on which fixture is used and the specimen's placement. Thereby its size and how it can be mounted were important.

Another important need was that the accelerometer had to be easy to use. As mentioned earlier, the engineers meant to use the shock tester could not be expected to have any deep prior knowledge or experience of this type of measurements. It might also be several weeks or months between the times an engineer uses the shock tester. Therefore, using the accelerometer needs to be as straight forward as possible.

5.1 The Target Specifications

An initial, shorter list of target specifications for the accelerometer was presented in Chapter 3.3, Table 3.4. This was solely based on the Customer needs. The list of target specifications is here extended to include all features of an accelerometer which were relevant to consider when choosing which accelerometer to acquire. The updated list of target specifications can be seen in Table 5.1.

Both an Ideal and an Acceptable limit were chosen in this case as well. The Acceptable values were the minimal performance needed to be able to measure the nominal shock pulse with sufficient resolution. An accelerometer with the Ideal specification values would have a significantly higher resolution and thereby be better suited to catch any potential short duration anomalies in the acceleration curve which might occur during the concept testing phase. Although, were to place this Ideal level is very difficult to estimate. Optimally the performance of the accelerometer should be as high as possible to be able to detect any unforeseen behavior, short duration vibrations, high g-load spikes, underlying resonance in physical structure, etc. Although higher performance generally cost more and often make the equipment more complex to use.

A relatively large portion of this thesis was spent in researching this subject to get a good enough understanding of how these measuring systems function to then be able to choose a suitable accelerometer for the STE. Focus for this thesis is placed on the development of the mechanical parts of the shock testing equipment. The accelerometer is an important part for the overall function of the STE, but it’s a purchased item and a more detailed explanation of the steps taken as part of the choosing the accelerometer and its specifications were therefore deemed needless for this report.

Table 5.1, Target specification for the accelerometer.

		Ideal	*Acceptable*
1.	**Type of sensor**	PR	MEMS or PE
2.	**Number of axis's**	3	1
3.	**Dynamic Range** The ± maximum amplitude it can measure	500 g	200 g
4.	**Frequency Response** The maximum frequency it can reliably measure. The output signal remains within a specified deviation, typically ±5% from the nominal output.	2000 Hz	500 Hz
5.	**Sample rate** It needs to have at least 10x the frequency measured to get an adequate resolution [5]	20 kHz	2 kHz
6.	**Low pass filter** With a cut-off frequency of	Bessel filter. With adjustable steps. ≥250 Hz	≥250 Hz
7.	**Data resolution**	≥13 bit	12 bit
8.	**Max. dimensions** (LxWxH)	25x25x10 mm	100x100x50 mm
9.	**Max. weight**	50 gram	500 gram
10.	**Easy to use.** Assessment needed. HW team at Verisure should easily understand it.	Plug & play. Intuitive. No instructions needed.	Written instructions needed when using it.
11.	**Data acquisition method**	Direct connection to PC. USB or wireless.	Amplifier with a separate accelerometer unit
12.	**Need for recalibration** How often it needs to be recalibrated by the manufacturer, or an external company	Never. Or ones every 3 years	1/year
13.	**Cost of the accelerometer** Including software.	≤10.000 SEK	≤20.000 SEK

5.2 The Selection Process

Several accelerometers were considered and compared in the same way as when comparing the shock-testing machines in the previous chapter. A table of all accelerometers considered for this project can be seen in Appendix C. The number of accelerometers included in this benchmarking became limited by the amount of time which could reasonably be allotted this task. The accelerometers included stems from a broad internet search and through contact with suppliers.

Focus was mainly placed on the "data logger" type of accelerometers. Although the norm when measuring a shock pulse is to use an accelerometer setup with a separate sensor, amplifier and/or "Data acquisition unit" (DAQ). This type of system is commonly used in a lab environment and generally offers both excellent accuracy and resolution. Although, it's also generally a quite complex and expensive setup. Therefore, accelerometer setups of this type were included in the benchmarking but avoided if possible due to their complexity.

The data logger type is instead focused on measurements performed outside of a lab. Here the sensor, amplifier and data storage are all combined into one unit. For this type of accelerometer, the accelerometer is meant to be mounted to the product or machine in question and measures the vibration and shocks it receives under real world conditions. The benefit of this type of unit is that it is often aimed towards less complex test setups with fewer parameters to take into consideration. It's often more of a "plug and play" type of equipment, which in this case was highly desirable.

The selection process consisted of discussing the different options with project supervisors at Verisure and comparing the different accelerometers relative to the parameters in Table 5.1. Spending the time to create a full decision matrix or creating a scoring system was deemed excessive in this case as the viable options were few and were easy to overview as it were.

5.2.1 **The Slam Stick C**

The chosen accelerometer was the Slam Stick C from Mide Technology. It's a data-logger type of accelerometer with a capacitive MEMS sensor. It's a tri-axial, 200 g sensor and with a sampling frequency of 3.2 kHz. Thereby it has sufficient resolution to measure the intended shock pulse and fulfilled all the necessary requirements in Table 5.1.

The reason for choosing this accelerometer was in large part due to its ease of use as it's targeted mainly towards a non-expert user, as well as its comparatively low cost. The focus on it being easy to use was both to benefit the end-user and also so it requires minimal time to get up and running resulting in more time for the remaining process.

It was also chosen for its compact form factor and the option of mounting it with either screw or double-sided tape, thereby making it easier to find a suitable place to mount it close to the specimen being tested.

Another benefit with a capacitive MEMS senor is that it doesn't need to be recalibrated as often as the other type of sensor. Thereby it requires less maintenance over its lifetime, i.e. it would need to be sent back to the manufacturer for recalibrated less often.

The tradeoff was that several of the specifications did not reach the Ideal limits set in Table 5.1. Although the accelerometer is sufficient to measure the nominal shock pulse, it might not have enough resolution to correctly measure any unexpected vibrations or movement in the test equipment which could interfere with the measurement. Thereby possibly hindering the ability to correctly determining the cause of these vibrations. This is mainly due to the lower than ideal sampling rate and the limited choice in filter type and cut-off frequency in the Slam Stick C. Although this compromise was estimated as acceptable based on the acquired knowledge at that time.

Figure 5.1, The Slam Stick C from Mide Technology [12].

6 Concept Generation and Selection

The concept generation and selection method were done in several steps to reach a final design. This step-by-step process and the concepts it generated are described in this chapter.

The concept generation and selection processes were done in two phases. In the first phase (steps 1-3), the more general design decisions were made. This meant deciding what type of shock-testing equipment it should be and what the overall mechanism for generating the shock should be. It was chosen to do the development process in two phases, first to narrow the scope considerably and thereby reduce the workload in the second phase (steps 4-7) when generating concepts for all subproblems. These concepts could then be combined into a complete product and systematically explored until arriving at a final design. Small scale concept testing was also included as part of the selection process. The entire process was based on the concept development process described by Ulrich and Eppinger [4]. Although the order of concept generation, selection and testing were moved around to better fit this project.

The different steps were as follow

1. Clarifying the problem and decompose it into subproblems
2. Defining the central subproblems
    a. External and internal search
3. Concept screening to define what type of machine the STE shall be based around
4. Concept generation for all subproblems
    a. External and internal search
5. Explore systematically
6. Concept testing
7. Concept scoring and selection of the final design

6.1 Clarifying the Problem

The overall problem is that the shock tester needs to be less complex and more compact compared to the commercially available machines, but still produce shock pulses with a quality close enough to a commercial machine. Thereby the shock pulse it produces should be within, or close enough to the certification standard's tolerances. It should also be consistent enough so that a reliable comparison can be made when testing different versions of a product.

To produce a consistent shock pulse, the motion of the carriage with the specimen must also be very consistent. Thereby the frame, carriage and fixture have to be stiff enough to not flex or move in any undesirable way during the shock event. This since it can interfere with the accelerometer measurement and also since it could affect the amount of fiction between moving parts making the motion of the carriage less consistent. Yet the parts need to be relatively light weight so that the STE is moveable and to keep cost down.

The shock amplitude needs to be variable considering that the characteristics of the programmer needs to be variable as well as that the amount of potential energy put into the impact. Therefore, the STE need a way to set these variables to predetermined values depending on the what shock profile is needed for each test.

The overall design should also be constructed so that the STE can be easily modified, and new functionalities can be added. This is needed as the customer in this case preferred to get a functional prototype and then empirically test and modify it until a satisfactory performance is reached.

6.1.1 **Design delimitation**

To minimize the potential maintenance as well as keeping the workload of this thesis to a reasonable level, it was chosen that the design should not use any complex machinery or computer aided solutions such as electromagnets, pneumatic control systems, etc. The STE should preferably only use manual work, gravity and other "low-tech" solution such as springs, bungee cords etc. to achieve the needed acceleration and braking.

6.1.2 **Problem decomposition**

The complex problem of designing the entire STE was decomposed into smaller and more manageable subproblems. The decomposition was based on the functionality of different components in a generic shock-testing machine, as described in the international standard for Testing machines for Mechanical shock [6].

The subproblems are as follow

1. A means to store the potential energy necessary for imparting the shock, i.e. a way to achieve impact velocity. It must be variable to achieve predefined g-load and pulse duration.
2. A way to control the movement of the carriage so that the forces applied only occur along one axis.
3. A pulse-shaping mechanism. I.e. a way to create the half sine shock pulse. Often called the “programmer”. Must be variable depending on specimen weight and the intended g-load and pulse duration.
4. A “reaction mass” (or “impact block”). A way to absorb the shock in a controlled and safe way.
5. A rigid table or carriage with means of attaching the fixture and specimen. It must be stiff and rigid enough to handle the shock with minimal flexing.
6. A fixture on which the specimen can be mounted in all 6 orientations. It must also be rigid enough to handle the shock with minimal flexing.
7. A safety system. A way to lock and release the carriage from the “raised” position where the potential energy is loaded in preparation of the shock.
8. A way to avoid multiple impacts. A braking system to stop the carriages motion after the shock.

6.2 The Four Central Subproblems

Initial focus was placed on the subproblems which would have the biggest impact on the STE’s overall design and functionality. Subproblem 1-4 from the list above were those deemed most central, those which together would make up the base of the STE. The other subproblems were those which would have less significant impact on other parts of the STE and which could be tackled later on, after the central subproblems were solved.

The goal in this first phase was to make broader design decisions for the STE in preparation for the more detailed concept generation in the second phase.

6.2.1 Internal and external search

The internal search consisted mainly of brainstorming and discussion with employees at Verisure.

The external search stemmed mainly from the market evaluation performed in Chapter 4 as well as literature describing the more general principle behind shock generation and measurements, see [5] and [7]. A patent search was also done, although yielding little useful information.

Due to delimitation set previously, the shock will be created by using an impact type shock machine where the carriage is given a velocity before impacting a "programmer" which formats the acceleration to the desired shape.

The motion of the carriage during the shock, i.e. while it's in contact with the programmer, constitutes a linear mass-spring-dampener system with one-degree of freedom, see Figure 6.1a. The force applied to the carriage depends on the relative position and motion of the carriage and the programmer's damping coefficient *c* and spring constant *k* [5]. The damping and spring coefficient can in this case be assumed to be constant.

To generate a perfect half-sine shock pulse, one needs a perfect rebound, thereby no dampening in the programmer so as the carriage leaves with the same velocity as it impacted. Although this is never the case, all materials have at least some dampening [5].

If an impact block (also called reaction mass) is added to the equation, then this will result in a more complex overall design and make the work of selecting and designing components which together can produce the needed pulse shape much harder. The force imparted on the carriage would then depend on the interaction between both spring-dampeners as well as the mass of the impact block, see Figure 6.1b. It's therefore beneficial if an overall design can be found where an impact block is not needed.

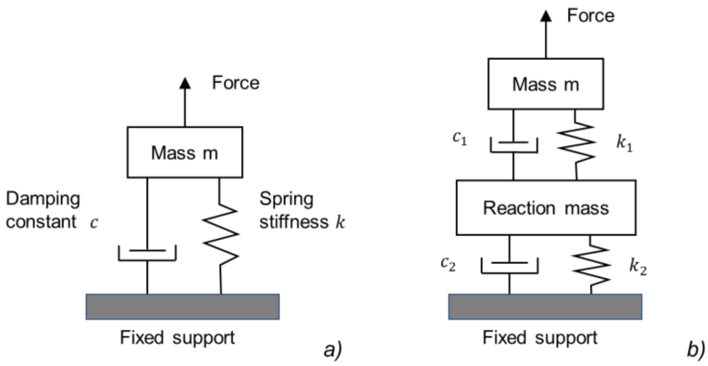

Figure 6.1, Mass-spring-damper system

6.2.1.1 Generating the potential energy and controlling the motion

From this external and internal search, four general designs of the machine were considered which would only need "low tech" mechanics to function. Figure 6.2 shows these four designs. All but the Horizontal slider design would use gravity as the main way to achieve the impact velocity. Springs or bungee cords could be added to further the accelerate the carriage thereby allowing the STE to be made smaller. The horizontal sliding design would need springs or bungee cords to accelerate the carriage. The use of a pneumatic cylinder to push the sled were also considered. In this case a small tank would be pressurized to a predetermined value, either by hand or using a small compressor, before releasing it into the cylinder.

The benefit of horizontal impact, as in the pendulum and horizontal slider design, is that the force from the impact would not be transmitted directly into the floor or table. Therefore, less consideration is needed concerning protecting the floor or table surface.

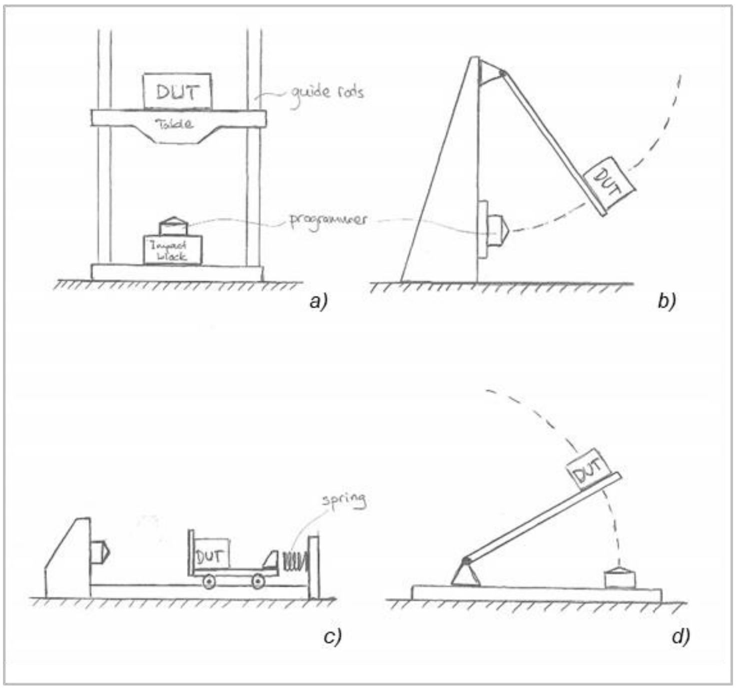

Figure 6.2, The four types of machine.

6.2.1.2 Pulse shaping

To obtain the shock pulse, both the use of a cylinder made from an elastic material such as polyurethane (PU) as well as a coil spring was considered. Either one or several of these programmers could be used.

A set of these programmers with different sizes and hardness values would then be needed to be able to vary the duration of the pulse relative to the carriage weight.

Basically all machines evaluated in Chapter 4 use a programmer consisting of a PU cylinder, or of a similar material, when producing shock in the range of 6 ms. The use of a coil spring was considered since to produce a perfect sine wave one needs a programmer with zero dampening, and here a metal spring is beneficial as it generally has considerably less dampening then an elastic material such as PU [5].

6.2.1.3 Reaction mass

The use of a reaction mass is especially important for the Free Fall and Inverted Pendulum design to protect the floor or table surface. However, in the Pendulum and Horizontal Slider designs the reaction mass' would work to dampen out the shock and avoid that the whole STE from moving or "jumping" as this movement risk interfering with the test result.

The preferred choice would be if the STE could function without the need of a reaction mass as it would simplify the design and manufacture of the STE considerably. This would be achieved by reducing the weight of the carriage and by ensuring that the force is spread out as much as possible when transferred to the surface below.

Another option is the conventional method, to use a heavy metal block suspended either on coil springs or rubber dampeners normally used to reduce vibration on large machines. The block would either be a solid piece of metal or consist of several plates bolted together to be able to vary the weight when calibrating the STE.

A third option considered was to design the frame of the STE such as it could flex a little and thereby reduce the peak load enough to within acceptable levels.

The last option considered was to ensure that the STE had a large footprint and to place the entire STE onto a thick rubber mat. Similar to rubber mats used by weight lifters. This would turn the mat into the secondary spring-dampener in Figure 6.1 and the entire frame of the STE would act as the reaction mass. The dampening effect would then depend on the material hardness and the STE's surface area.

For the Pendulum and Horizontal slider designs, the option to place the STE against a sturdy wall to further reduce the risk of it moving when the carriage impact was also considered.

A combination table of all solutions to the central subproblems can be seen in Table 6.1 below.

Table 6.1, Combination table of solutions considered for the four central subproblems

Generating the potential energy necessary for imparting the shock	Controlling the carriage movement	Pulse-shaping i.e. the programmer	Reaction mass
Free fall	Guide rods and linear bearings	PU cylinder	Metal block suspended on springs or rubber dampers
Bungee cords	Pendulum arc	Coil spring	No reaction mass Wide footprint
Compressed springs	Inverted pendulum		Flexing frame
Pneumatic cylinder			Foam or rubber mat

6.2.2 **Drop height and impact velocity relative to rebound**

The velocity needed to achieve the predefined peak acceleration is dependent on the rebound velocity of the carriage after impact. The half-sine shock curve when defined by the acceleration equals Equation (6.1) where $\Omega = \pi/D$ and D is the pulse duration, see Figure 6.3.

$$\boldsymbol{a}(\boldsymbol{t}) = \hat{\boldsymbol{a}}\,\boldsymbol{sin}(\boldsymbol{\Omega t}) \tag{6.1}$$

The velocity change of the carriage which occur during the shock pulse is equal to the area under the curve and remains constant for a given amplitude and pulse duration, as described by Lalanne in [5]. This velocity change is the difference between the carriage's velocity when impacting the programmer (v_i) and when leaving the programmer, its rebound velocity (v_r). The rebound velocity is in turn dependent on the material properties of the programmer and can theoretically vary between 0-100% of v_i. The amount of rebound is denoted by the coefficient of restitution (α).

$$\Delta \boldsymbol{V} = |\boldsymbol{v_r} - \boldsymbol{v_i}| \tag{6.2}$$

$$\boldsymbol{v_r} = -\boldsymbol{\alpha} * \boldsymbol{v_i} \tag{6.3}$$

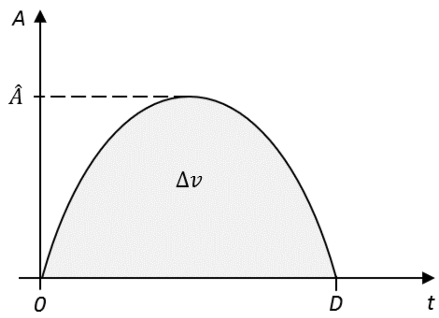

Figure 6.3, A half sine curve

The highest theoretical impact velocity needed will thereby occur when the rebound is zero. Although the rebound for elastic material such as PU often vary between 25-75% [7]. In short, a lower rebound value requires a higher impact velocity to achieve the same shock pulse. The drop height needed to achieve impact velocity using only gravity can then be deduced. Table 6.2 shows the drop height needed in this case depending on the programmer's rebound. The last point in Table 6.2 was added to illustrate what drop height might be needed in the case of testing a specimen to find its weakest point.

$$\boldsymbol{h_d = \frac{v_i^2}{2g}} \tag{6.4}$$

Table 6.2, Drop height and impact velocity depending on rebound

	Peak acceleration (g)	***Pulse duration (ms)***	***Rebound (%)***	***Velocity change (m/s)***	***Impact velocity (m/s)***	***Drop height (m)***
1.	100	6	75	3.82	2.18	**0.24**
2.	100	6	25	3.82	3.06	**0.48**
3.	150	6	50	5.73	3.81	**0.74**

The conclusion from this was that the distance needed to achieve necessary impact velocity could be done using gravity alone while staying within the target specifications for STE dimension. Thereby no extra springs or bungee cords was necessary. This was applicable for the Free fall, Pendulum and Inverted pendulum design.

6.2.3 The need for an impact block or not

The advantage in this case is that the test parameters have a quite narrow range and both the specimens' weight and the g-load are relatively low. Thereby the STE will only have to handle relatively low forces compared to what most commercial machines are designed for. To make an initial judgement whether the choice of not using an impact block to protect the underlying surface is feasible, a quick and simple comparison was used.

Assuming a case at the upper range of test parameter where the carriage, fixture and specimen have a combined mass of 10 kg and the peak acceleration of the shock is 140 g. This would equal almost 1400 kg at the absolute peak and an average close to 1000 kg for 6 ms.

Looking at a common, everyday chair with thin metal legs of 1.6 cm in diameter. Assuming two persons, one sitting in the lap of the other, equaling 150 kg sits on it. The static pressure from this equal approximately 1.8 MPa, or 19 kg/cm^2.

To equal this amount of pressure at peak load (1400 kg), the shock tester would only need 4 feet with a diameter of 4.8 cm. But comparing an impact load to a static load is not all too correct as most materials react slightly different depending on how fast the load is applied and the duration of it. Although this comparison gave enough of an estimate to deem the solution as feasible to move ahead with. It should also be noted that this shock tester will be placed on a floor with a concrete substructure.

6.3 Concept Screening to Define the Overall Design

A selection of which of the solutions shown in Table 6.1 to use was made based on the limited findings made in previous chapter and the information acquired during the market evaluation. To save time and keep project moving the selection was made based on intuition instead of making a time consuming scoring system.

The chosen combination was to base the general design around a Free Fall Drop Tower design using only gravity to accelerate the carriage. Both pendulum designs, although novel and compact, had too many unknowns. For instance, the effect of using a rotational motion instead of a straight motion before impact as well as the possible need of a suspended impact block to avoid the risk that the STE "jump". The Free Fall Drop Tower design with a frame to guide the motion was deemed a safer bet, a proven and more widely used design.

Both solutions, the PU-cylinder and Coil spring, as a programmer was chosen since no conclusive choice could be made at the time.

For the Reaction mass, the decision was to not use one, but instead focus on incorporate some flex into the design, mainly to protect the STE itself. Focus should also be placed on giving the STE a large footprint to reduce the peak pressure on the underlying surface.

6.4 Concept Generation for all Subproblems

Concepts combining solutions for the four central subproblems where made to simplify the process as these four forms the base of the STE. However, many of the features for solving a specific subproblem could be used in the concept designs as well.

The aim when building the STE was to take that process in steps, solving one problem at a time. The idea was that the first prototype build would focus on solving the primary functions of the STE, i.e. the first 6 subproblems listed in Chapter 6.1.2, and get those functions up to a satisfactory performance. A Braking system and a Lock and release system from subproblem 7 and 8 were deemed as secondary features and the plan would be to add these functions at a later date, after this thesis. Detailed concepts for those are therefore not included in this thesis. Although the features were taken into consideration when designing the rest of the STE, making sure there is space and the possibility to add these features later on.

Up until that moment, the carriage would have to be dropped manually and multiple impact was acceptable since no specimen would be tested during that period. This decision was made together with the project supervisor at Verisure.

6.4.1 **Concepts for the four central subproblems**

Concepts solving the first four subproblems of Achieve impact velocity, Guiding the motion, Pulse shaping using a programmer and Absorbing the shock.

Focus throughout was placed on having a ridged yet simple construction. This to thereby achieve a consistent and controlled fall of the carriage, which in turn should make the shock generation consistent and reliable. In all concepts the pulse amplitude is set by the drop height.

6.4.1.1 Concept 1A: Steel tube frame and linear bearings

A steel tube frame bolted and welded together. The frame support two steel guide rods for the carriage to move along. A clamp around one of the guide rods act as a stop block when raising the carriage to the intended drop height.

A steel base plate is bolted to the base frame on which the programmer is mounted. The steel frame and the thick base plate adds weight close to ground ensuring a stable STE. Height adjustable rubber foot in all four corners ensure that the STE is level.

The vertical legs are slid into and bolted to collars on the lower frame. The collar is made from a large dimension of steel tube. This would allow the upper frame, the guide rods and the carriage to be easily disassembled before being stored away when the STE is not in use.

Several holes along one of the vertical steel tubes allows a stop block to be attached at predetermined intervals housing a lock and release mechanism. A brake mechanism would be mounted to the carriage and brake against the guide rods.

Two options for the programmer. Either a single PU-programmer in the center of the base plate or using two coil springs around the guide rods. The PU-programmer would be adhered to a small plate which in turn is bolted to the base plate.

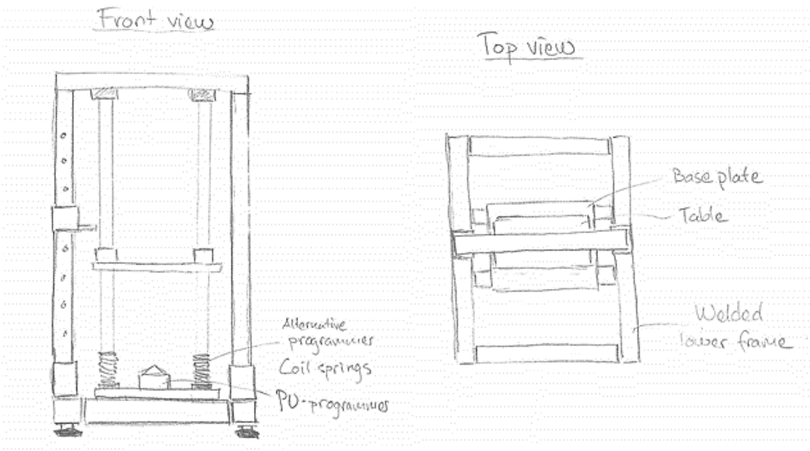

Figure 6.4, Concept 1A

6.4.1.2 Concept 1B: Aluminum profile frame

Similar to the previous concept but using aluminum profiles for the frame. The lower frame would be made from larger dimension profiles to ensure it can handle the impact loads. Wheel assemblies bolted to the carriage run along the groves and edges of the aluminum profile frame, using standard wheels made for these aluminum profiles.

Using a mounted ruler or markings on the frame together with a stop block running in the track of the aluminum profile to set the drop height. The lock and release mechanism could be mounted in the same way. Braking mechanism mounted to the carriage could use brake pads which engage after the impact and slide against the flat surfaces on the frame.

Height adjustable rubber feet in the corners. Extra weights could be added to outer ends of the lower frame if more stability is needed.

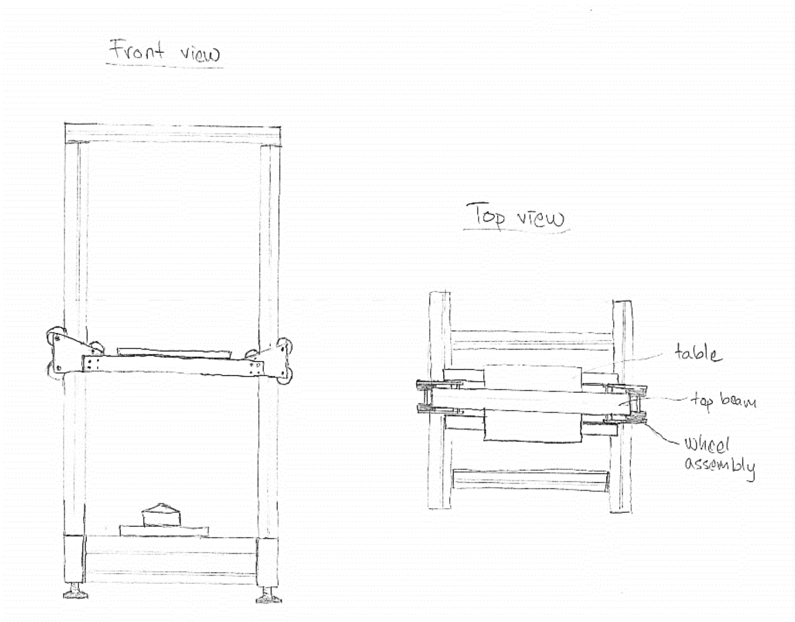

Figure 6.5, Concept 1B

6.4.1.3 Concept 1C: Three-legged design

A thick steel plate function as the base of the STE. Thick steel rods as guide rails provide the strength and stiffness ensuring a controlled motion of the carriage. The guide rods are mounted and bolted into metal sleeves with welded ribs. These are in turn bolted to metal plate with slightly oversized holes making the them sideways adjustable. A thick rubber mat under the whole plate acts to dampen the shock and gives the STE a wide foot print.

The programmer is a solid PU-cylinder placed in the middle.

The drop height indicator as well as the lock and release mechanism are placed on a third using for instance an impact activated linear ratchet mechanism which locks the carriage in place on the way up. This would also ensure that the carriage can't be dropped by accident. Alternatively, can clamps around the guide rods be used for setting the drop height. A bar connects the top of the guide rod and the third leg giving the STE added stiffness.

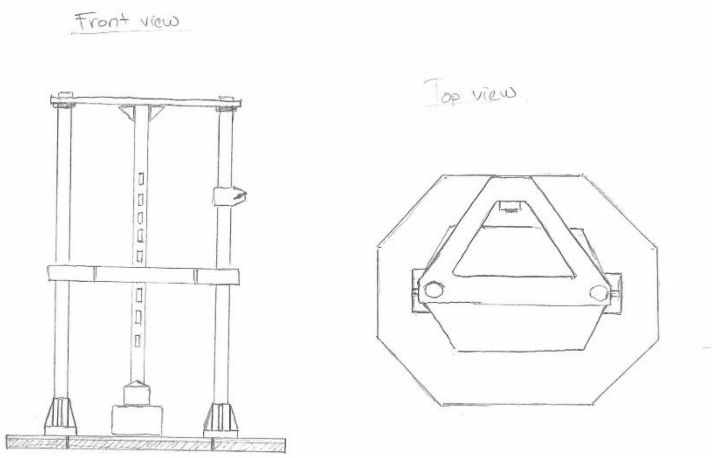

Figure 6.6, Concept 1C

6.4.1.4 Concept 1D: Single beam with linear rail

A large square steel tube, or beam, is bolted to a thick steel plate. A rubber mat is again placed under the whole plate to absorb and spread out the shock. Angular bracket help stabilize the steel beam. A single linear rail is bolted to the beam. The table is in turn mounted to the sled of the linear rail.

The table has both a vertical and horizontal surface on which to mount the specimen. Angled side plate help making the table ridged enough.

A secondary sled, above the table carriage, with a locking mechanism functions both as a height indicator and housed the lock and release mechanism.

A single PU-cylinder, mounted to base plate, function as the programmer.

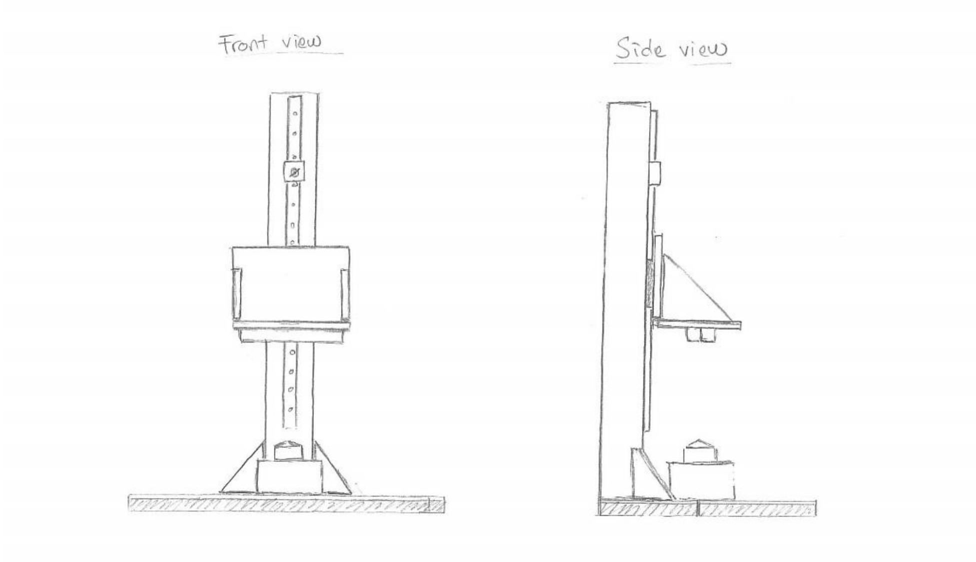

Figure 6.7, Concept 1D

6.4.2 **Table design**

All concepts are all focused around designs where all or most of the parts are made from aluminum since the table needs to be very stiff and ridged to get shock tests with high reproducibility, yet as light as possible to reduce the stress on the rest of the STE. A necessity is also to have a flat surface where the table impacts the programmer.

The mounting points on the side of the table depends on the type of guide rail solution used. Therefore, this part of the concepts can be changed depending on which combination of concepts are selected.

The mounting points for the fixture not included in any of the concept drawings. Although the three potential solutions are the same for all concepts. Either, holes will be drilled and threaded when needed or a grid of threaded holes across the whole surface is used. The last solution involves having several parallel dove tail grooves across the surface in which screw blocks can be slid, which in turn the fixture can be mounted.

6.4.2.1 Concept 2A

A solid aluminum beam on which the linear bearings or similar component can be mounted. Triangular cross beams made from thick aluminum plate to support the whole table surface. These are bolted to both the beam and to the aluminum plate above it.

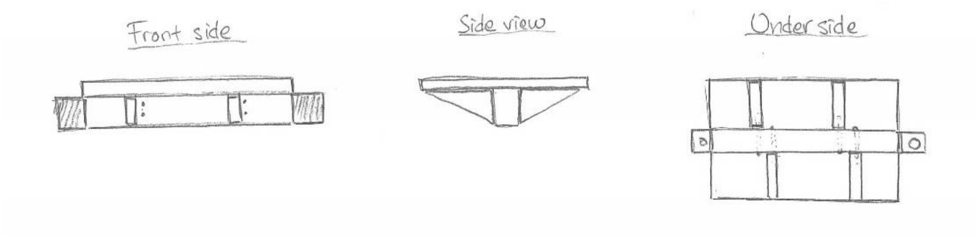

Figure 6.8, Concept 2A

6.4.2.2 Concept 2B

Two rectangular aluminum tubes bolted together to make one wide central beam. A thick aluminum plate as the table surface is bolted to it.

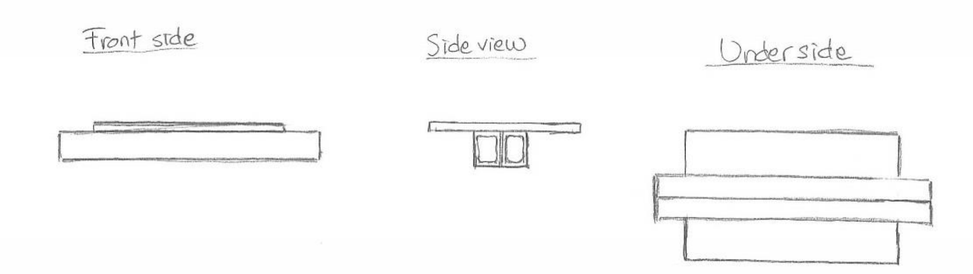

Figure 6.9, Concept 2B

6.4.2.3 Concept 2C

Square aluminum profiles make out the frame of the table. The two middle beams support a circular aluminum strike plate which impacts the programmer. The two side beams ensure that the whole width of the surface is supported. A linear bearing or similar component can be mounted to the track running along the side beams.

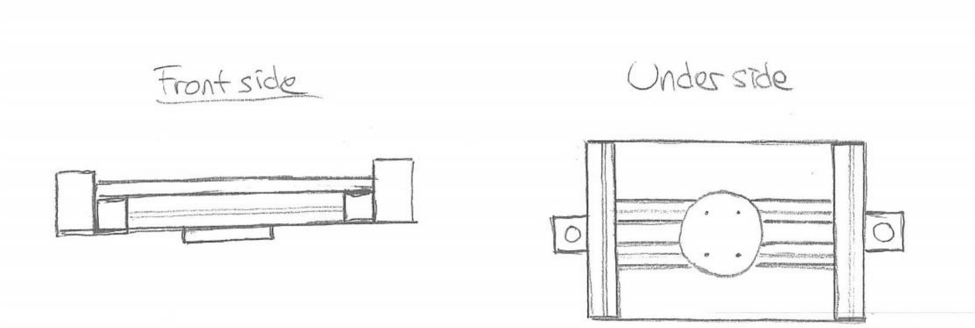

Figure 6.10, Concept 2C

6.4.2.4 Concept 2D

Several plates with decreasing surface area are bolted together. Thereby it's thickest in the center where the impact with the programmer occurs and where most of the mass from the specimen and fixture are located.

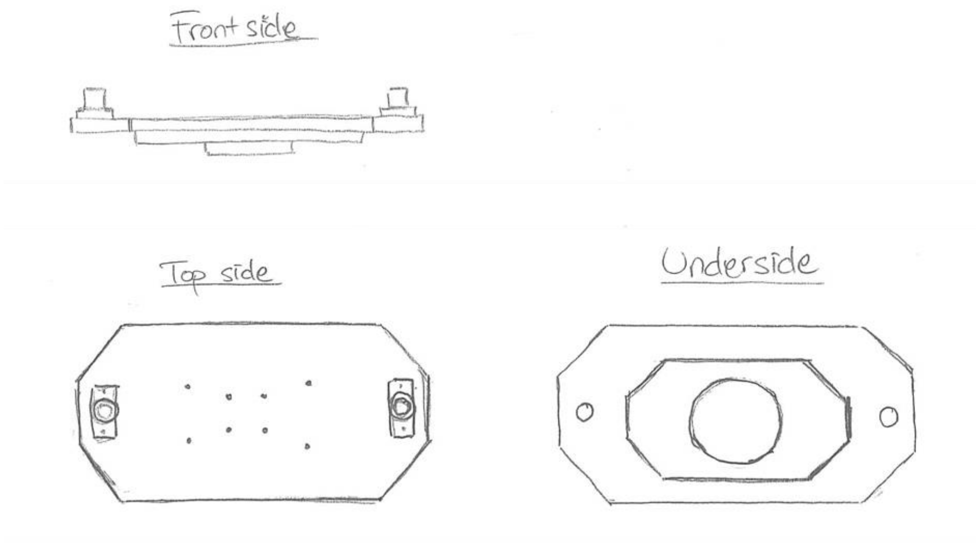

Figure 6.11, Concept 2D

6.4.3 **Fixture**

The primary needs of a fixture are that a specimen with the maximum dimension specified in Table 3.2, Target specification for the shock tester. Variables based on the primary needs. can be securely mounted in the 5 orientations for testing shocks in ±X, ±Y and -Z. The fixture also has to be as stiff and rigid as possible to ensure that a uniformly shaped half-sine curve is produced and a high repeatability.

6.4.3.1 Concept 3A: Aluminum profile frame

The fixture is made from aluminum profiles and a 10mm aluminum plate. The plate is mounted to the two vertical beams. The horizontal beam is bolted to the table. The square plate can be taken off and rotated instead of rotation the specimen when testing the ±X and ±Y directions. Thereby only one set of mounting holes for the specimen is needed in the plate. The same plate can then be mounted on 4 vertical beams for when testing the specimen mounted upside down, in the -Z direction.

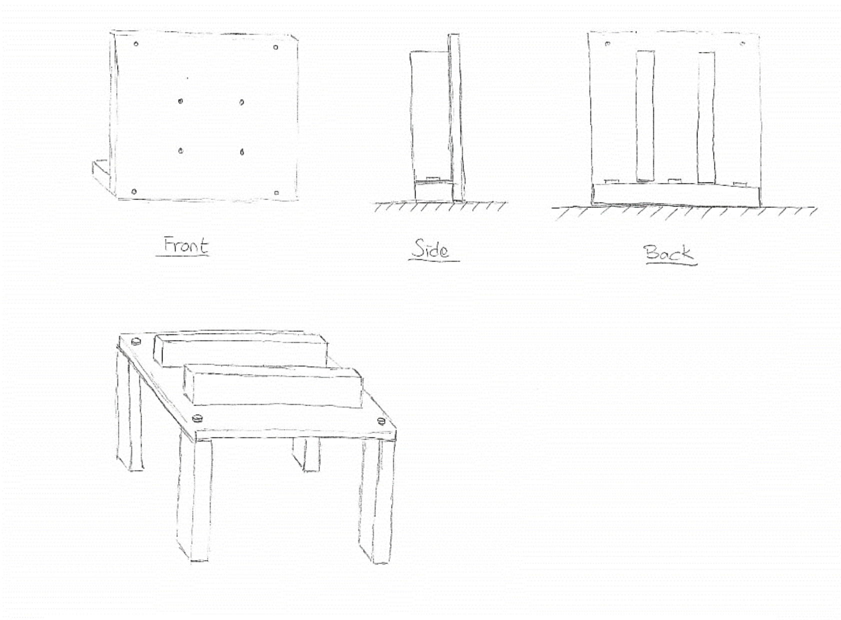

Figure 6.12, Concept 3A

6.4.3.2 Concept 3B: Two walled box

The fixture consists of two square aluminum plates bolted together with two aluminum profile beams on each side to make the construction ridged enough and to provide necessary mounting points for when placed on the side or when testing the specimen in -Z direction.

The fixture work for all 6 test directions by rotating the whole cube and bolting it to the table.

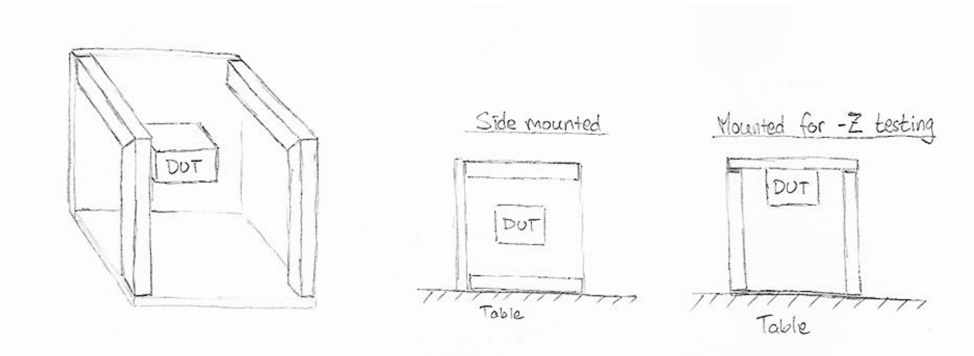

Figure 6.13, Concept 3B

6.4.3.3 Aluminum plate

Two triangular aluminum plates are bolted to the square aluminum plate and to the table via four brackets.

Figure 6.15 shows two alternatives for mounting the specimen upside down (-Z direction). The plate is mounted to the table with 4 threaded rods through several metal collars. The amount of metal collars determines the height of the plate. The height can therefore be adjusted to the specimen's dimension and thereby minimize the risk of the fixture swaying side to side.

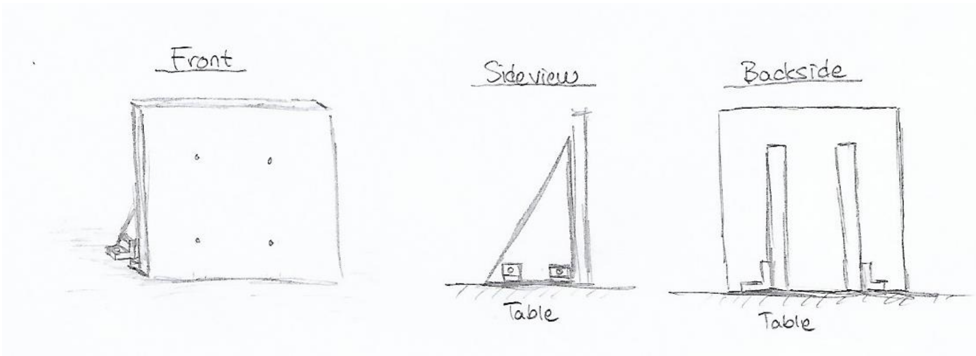

Figure 6.14, Concept 3C. For mounting when testing in ±X and ±Y.

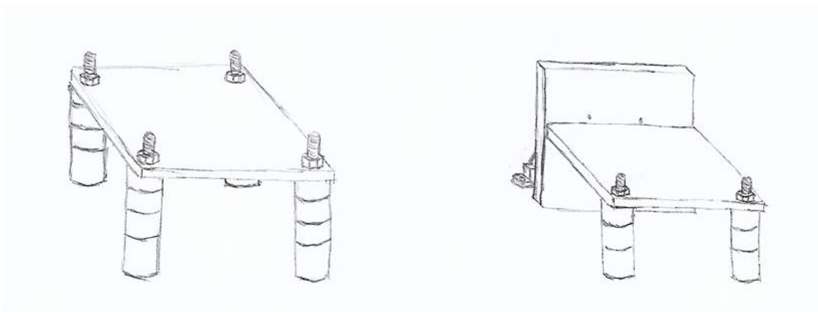

Figure 6.15, Concept 3C. Two alternatives for mounting when testing in -Z.

6.5 Concept Screening and Selection of the Final Design

The concept screening was done together with project supervisors. The different combination of concepts where discussed and weighed against each other based on the following parameters

- The design complexity and the estimated build time.
- How proven the solutions used in the design were. I.e. if they are used in other, similar machines.
- Frame and table stiffness, i.e. the shock repeatability.
- Robustness and reliability of the design.
- How easy it would be to modify and add new features to it.
- Cost.

The collective decision was made based mainly on intuition. The decision focused therefore primarily around the proven solutions and designs which would be easy to modify.

Final choice where a combination of concept 1B, 2C and 3A, but using the steel rods from Concept 1A as guide rails.

Thereby, it would be a test equipment which for simplicity would mainly be built from aluminum profiles. Both the frame, table and fixture. This were also the best choice if wanting to change the design later on.

Both the use of a single PU-programmer and the use of steel rods and linear bearings where chosen since it's by far the most common solution used among the commercial shock-testing machines of this type. Thereby the solutions are proven and a safe choice.

6.6 Concept Testing

A small-scale model of a Free Fall Drop Tower type of test setup was built to function as a general proof of concept. The rudimentary test setup can be seen in Figure 6.16 including only the most fundamental features of machine.

The test setup comprised of

- Two steel rods and linear bearings normally used in 3D-printers. With the option of using either generic linear ball bearing or an IGUS Drylin plastic bushing mounted in the bearing block. 3D-printed mounts held the guide rods in place.
- A 10 mm aluminum plate as a table on which the accelerometer was mounted.

- Two types of Polyurethane (PU) programmer were used. A PU-damper normally used in longboards, with hardness level of Shore 85A. The second one comprised of several layer of 2 mm, Shore 70A PU-sheets, adhered together.

The purpose was to test the general principle of generating a shock pulse and see if a half sine curve could be produced. It would help to understand how well the calculation for the simplified case of an ideal PU-programmers matched with the real world. The hope was also to potentially unearth any unexpected problems which would need to be addressed for a full-scale STE.

The table was raised and dropped by hand. A 3D-printed clamp around the one of the steel guide rods ensured that the drop height stayed consistent.

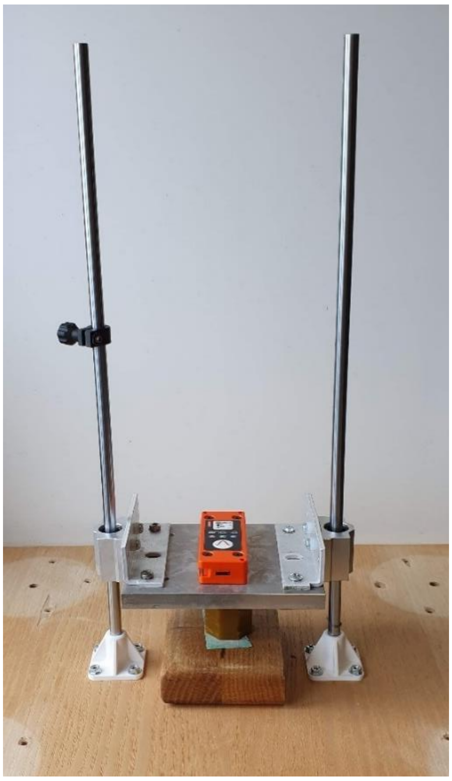

Figure 6.16, The small-scale test setup

6.6.1 **Programmer characteristics**

The two types of programmers can be seen in Figure 6.17. These were chosen since they were easy to find, were of the correct material and had dimensions which fit this small-scale test setup.

The idea behind the second programmer was to see if a programmer could be made from several sheets adhered together. The height would thereby be variable and there would be no need to order an expensive range of custom programmers made from solid PU.

Figure 6.17, The two test programmers

The process of calculating the programmer properties relative to the motion of the carriage follows the method described by Lalanne [5].

Assuming the ideal case where the PU-programmer has no damping and behaves as a perfect spring. Equation (6.5) describes the duration (t) of its natural sinusoidal oscillation based on its stiffness (k) and the mass of the carriage m_c. This is only valid during compression and relaxation of the programmer, i.e. as long as the carriage is in contact with the programmer. It equals the half sine pulse duration of the shock, i.e. $D = 0.5t$. The stiffness (k) necessary for the programmer to produce a certain shock pulse is then simply given with Equation (6.6). Thereby, in the ideal case, the needed stiffness depends only on the given pulse duration. The peak acceleration in turn depends, in the ideal case, only on the drop height, i.e. the impact velocity.

$$t = \frac{2\pi}{\omega} \quad where \quad \omega = \sqrt{\frac{k}{m_c}} \tag{6.5}$$

$$k = m_c \frac{\pi^2}{D^2} \tag{6.6}$$

Equation (6.7), as described by Lalanne [5], gives the spring stiffness (k) for a cylindrical programmer of an elastomeric material where E is Young's modulus (modulus of elasticity) of the material in compression and where A and h_{prog} is the cross-sectional area and height of the programmer.

$$k = \frac{E * A}{h_{prog}} \tag{6.7}$$

6.6.2 Shock tests using different programmers

The general test procedure consisted of dropping the table several times from a predetermined height and then evaluate the resulting shock curve compared to the calculated peak acceleration and pulse duration for the ideal case. This was done to both programmers and with varying height of the second programmer.

Figure 6.18 shows two shock tests using the first programmer at two different drop heights. These curve shapes are close to an ideal half sine curve. The pulse durations for the two curves have remained almost identical at different impact velocities, showing that in this respect, the use of the ideal case equations is a viable method. Note, the aim in these tests were not to achieve the nominal pulse shape of 100 g and 6 ms. The nominal and tolerance curves in Figure 6.18 are there just as a reference.

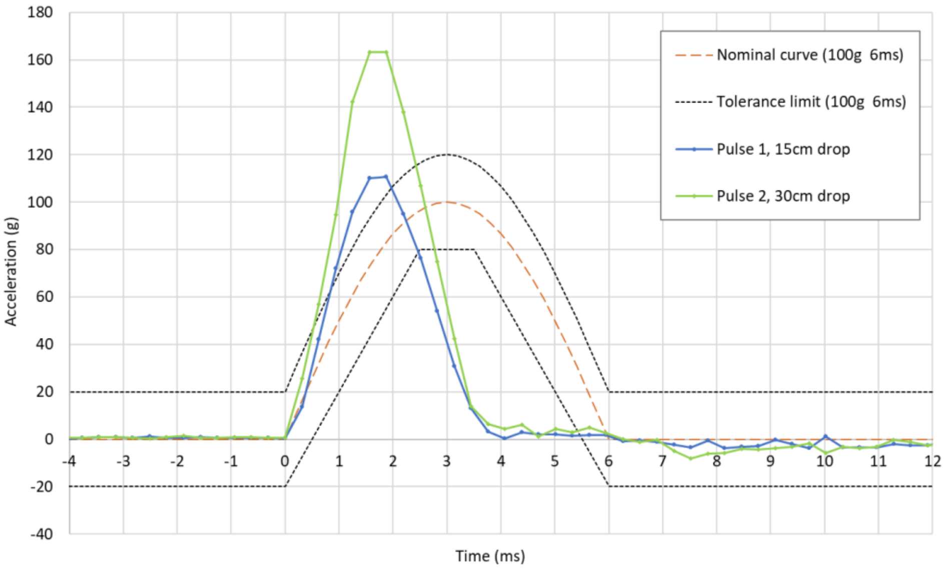

Figure 6.18, Shock test with the 1st programmer (the red longboard damper). The shock duration equal approx. 3.5 ms.

Figure 6.19 show three shock pulses when using the second programmer at 20 mm height and a constant drop height. The completely flat top of this programmer created a problem where when the flat table hits the flat programmer, a shock wave is sent through the programmer and reverberates several times back and forth to the carriage. This creates a high frequency oscillation which distorts the desired half-sine curve and showed up as the bump in curves immediately after $t = 0$. Unfortunately, the accelerometer's sample rate was in this case too low to catch the full effect of the shock wave, although it's clear that this is the cause. A depiction of this phenomena from [5] can be seen in Figure 6.20.

This confirmed the importance of having a slightly conical shaped top surface on the programmer as most manufacturers have on their programmers. The slightly conical top surface ensures that the two surfaces contacts each other gradually [5]. This phenomenon was not clearly present with the first programmer, probably due to it having a slightly slanted shape and a reduced top surface area due to the hole in the middle.

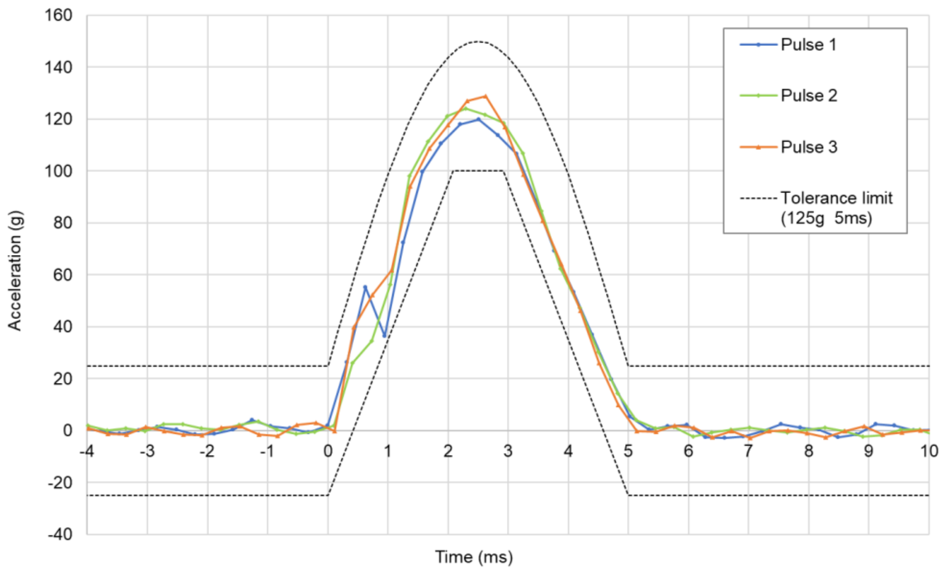

Figure 6.19, Programmer nr2, with 4 layers, 20 mm. Drop height 30 cm.

The slight variation in peak acceleration can be attributed to that the guide rails wasn't rigidly fastened at the top and the lack of a release mechanism which could drop the carriage more consistently than is possible by hand.

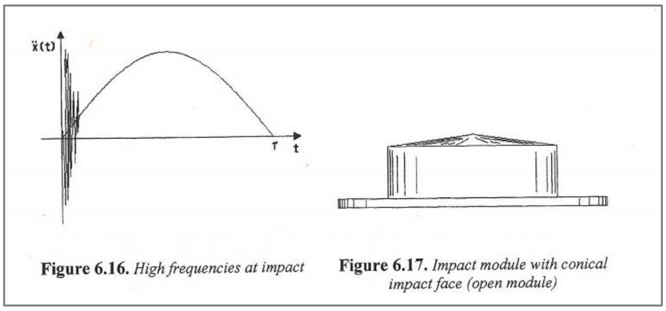

Figure 6.20, The effect on the measured shock curve caused by a rebounding shock wave through a flat top programmer as described and shown by Lalanne in [5].

The second programmer was also tested with double height thereby making it higher than it was wide with a ratio of 4:3. The result from this test is shown in Figure 6.21. These pulse curves are compared to previous results much more uneven and irregular. This is most likely due to the programmer's dimension which made it less stable and which allowed it to bend during compression.

To determine what peak amplitude and pulse duration the shock had, the tolerance and nominal curves are adjusted until they fit the shock pulses, as shown in Figure 6.21.

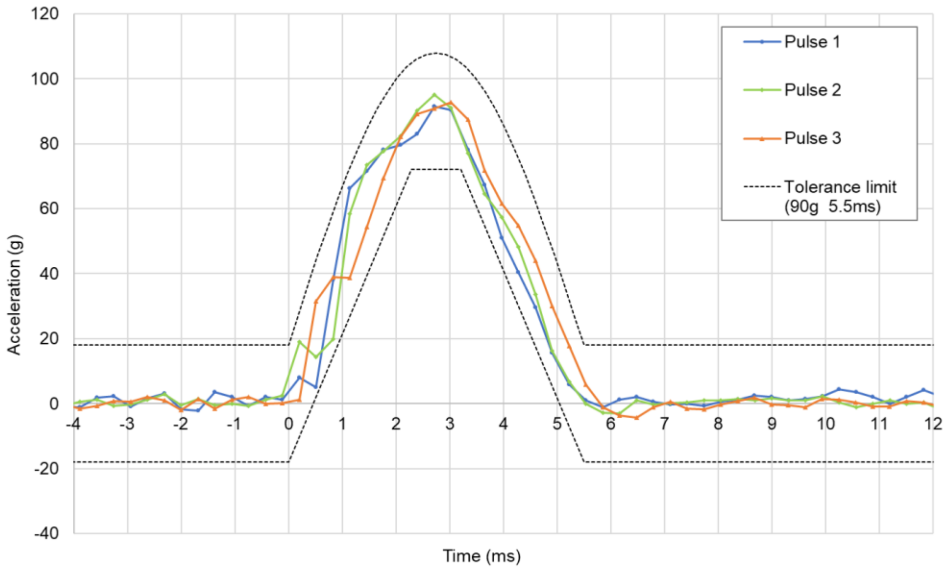

Figure 6.21, Shock tests with the 2nd programmer, but with 8 layers, 40 mm. 19 cm drop height. Tolerance lines adjusted to 90 g and 5.5 ms.

The downside of using "off the shelf" PU-products like the two programmers in this test are the lack of material data available. The necessary elasticity modulus (E) and the rebound value (α) cannot be reliably deduced from the commonly used hardness level measured in Shore A. Moreover, the Shore value is generally defined with a tolerance of ±5, which in this project can have a significant effect on the programmers expected performance. Material data from another manufacturer was therefore used here.

When comparing the calculated values of k from Equation (6.7) to the values based on the measured pulse duration from the graphs above using Equation (6.6), the values differed only 5-15%. Although, the values matched up for both programmers when accounting for a potential ±5 Shore A variability in the material. Thereby, the ideal case equations are sufficient to be used when dimensioning a programmer for the full-scale STE.

It was also found that the distance between the two guide rods relative to the distance of the furthest contact points in the bearings i.e. the bearing length was too large. This allowed the table to sometimes wedge itself slightly and "stick" to the guide rods while raising the table without keeping it perfectly level.

6.6.3 **Conclusions**

- A half sine curve within the given tolerances set by the IEC 60068-2-27 standard can be produced.
- The height to diameter ratio of the programmer should preferably be less than 1:1 to ensure that a uniformly shaped half sine curve is achieved.
- It's necessary for the programmer to have a slightly conical top to ensure a uniformly shaped half sine curve without distortion.
- The use of several layers of PU-sheets for a programmer worked, although it would be difficult to shape it into a slight conical top. The use of a solid piece of PU is preferred.
- The distance between the guide rods relative to the bearing height needs to less than the 6:1 ratio used here.

7 Detailed Product Development

Based on the final concept selected and tested in previous step of the development process, the next step was to further develop the concept into a complete CAD model. This chapter briefly describes the shock testers different components and their functionality. A short comparison with the finished prototype of the STE is also made.

The complete CAD model of the Shock tester is shown in Figure 7.1. Apart from a few specialized components, the STE is made from aluminum profiles and its associated connectors and fittings, and 10 mm aluminum plates. This simplified both when ordering the parts and when assembling the STE.

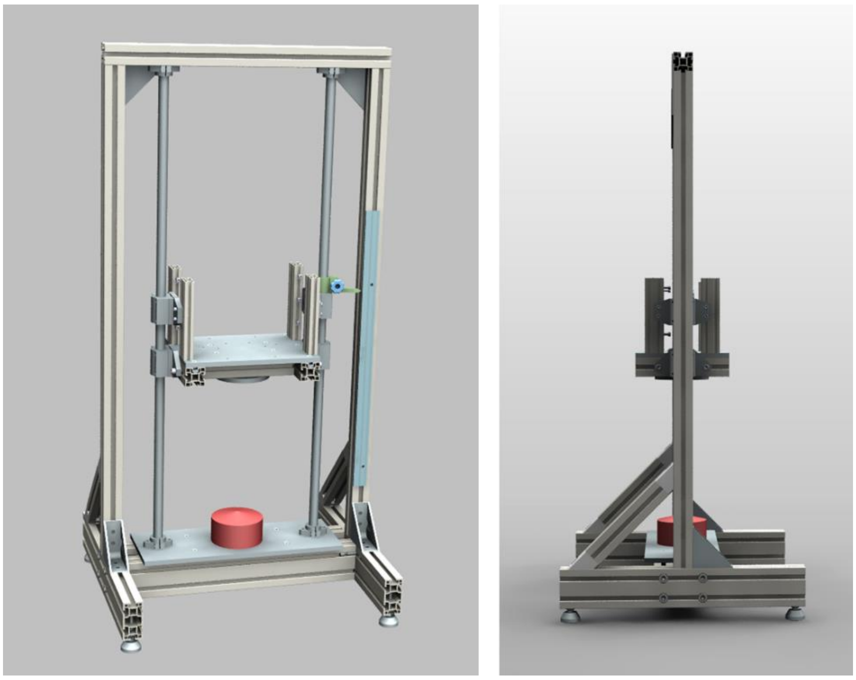

Figure 7.1, CAD model of the Shock tester.

7.1 The Components of the Shock Tester

An overview of the Shock testers different components can be seen in Figure 7.2 below. The thinking throughout was to oversize the parts and fittings where possible to ensure that the upper frame was rigid enough to ensure a smooth motion of the carriage and that the lower frame could handle the structural loads of repeated impacts.

All components were fastened with hex bolts, thereby it’s easy to disassemble and modify. New components can easily be fastened anywhere along the tracks in the aluminum profiles. The use of aluminum plates everywhere also makes it relatively easy to drill and tap new holes using hand held tools.

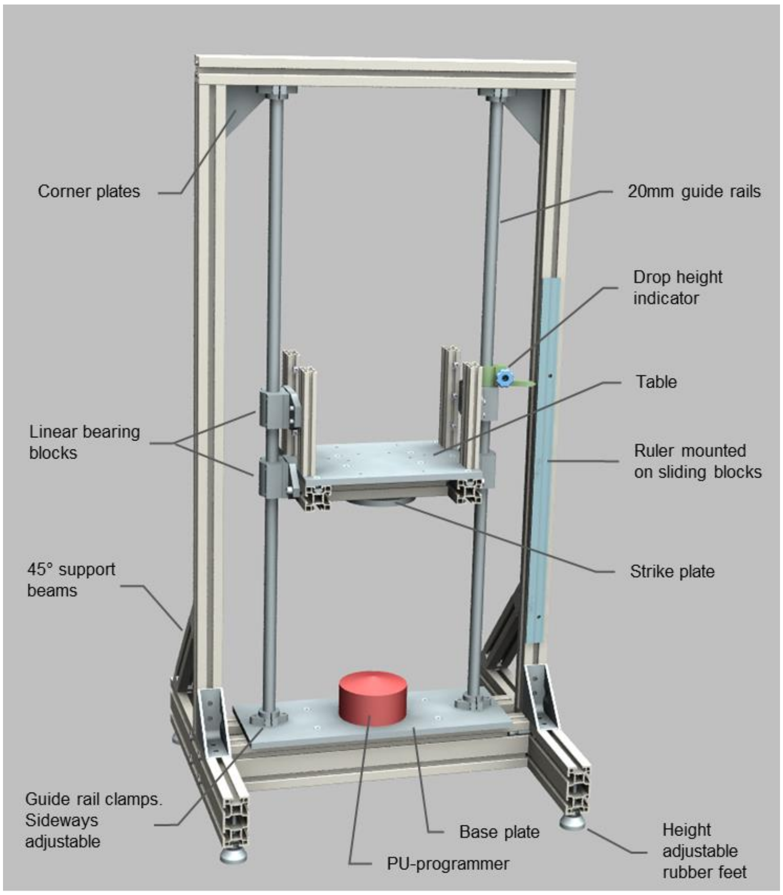

Figure 7.2, The main components of the Shock tester.

7.1.1 The frame and guide rails

The main area of concern for the frame was to ensure that the lower part of the frame was sufficiently strong to endure the impacts. A larger profile dimension was used on the four aluminum beams in the lower frame.

To get a rough estimate what size and number of beams would be needed to avoid too much flexing, the load was instead assumed as a static point load placed in the middle of the two center beams. Assuming the static load equaled the peak load of a 150 g, 6 ms and payload weight of 8 kg, then the center of the base plate would deflect approximately 0.65 mm. This was calculated using material data from the manufacturer. Although this flexing would affect the pulse shape a bit, it was deemed negligible compared to the programmers calculated compression distance of 7.1 mm needed to achieve that shock.

Another area of concern was the attachment points between the center and the side beams of the lower frame. The manufacturer was consulted and then the number of bolts they estimated would be sufficient was doubled.

By loosening 8 bolts between the upper and lower part of the frame, the whole upper frame can then be taken off. The guide rods and the carriage can then be lifted away as well, thereby reducing its size when storing the STE somewhere else when not in use. As the guide rod clamps and frame brackets remain fastened to the frame, all components will be correctly aligned when assembling it the next time.

The 45° support beams where only placed on the backside to give the user an open area on the front side.

To account for the different heights of the programmers, the metal ruler on the side of the STE can be slid up and down along the groove in the frame and then fastened by hand using two wing bolts.

The weight of the carriage (with fixture) is 7.4 kg and the rest of the STE weighs approximately 20 kg. If needed to make the STE stable, more weight could be added to the four arms of the lower frame.

As all parts were bolted together, the risk is thereby likely that the many will quickly loosen due to the vibrations. Spring washers where therefore used in all bolts with the added option of adding “thread locker” to the bolts if the washer isn’t enough.

7.1.2 **Table and fixture**

The vertical beams originally part of the fixture concept was made a permanent part of the table. This provided mounting point for the upper bearing which in turn helped stiffen the fixture.

Each pair of linear bearings where spaced a small distance apart from each other to ensure that the table slide smoothly since the ratio it's considerably larger than the 6:1 used in the concept testing.

The same fixture plate can be used for all 6 orientations as can be seen in Figure 7.3. The added benefit when fastened to the vertical beams is that it adds further stiffness to the table.

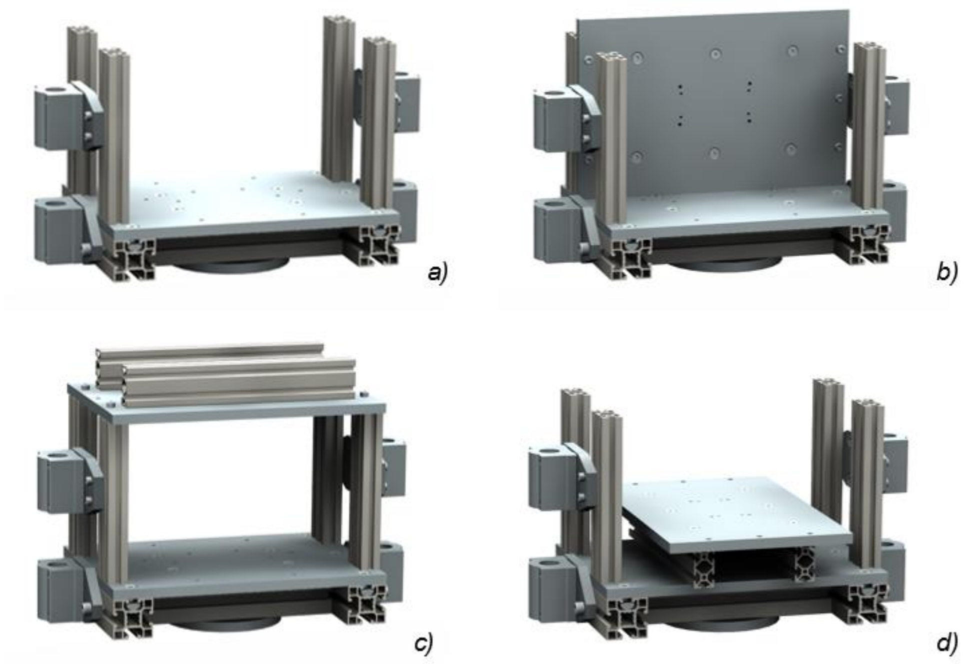

Figure 7.3, Table and fixture combinations. a) Table only, for +Z shock direction. b) 90° fixture, for testing ±Y and ±X direction. c) 180° fixture, for -Z direction, with the specimen mounted upside down. d) Alternative +Z direction, with the benefit that the carriage mass remains the same as for b and c.

The fixture plate is meant to be used as a sacrificial plate in where mounting holes for the specimens are drilled. When it has too many holes, the plate is replaced.

The two beams on the backside of the fixture plate is there to give it extra rigidity, especially when it's used for testing the specimen mounted upside down, as seen in Figure 7.3c.

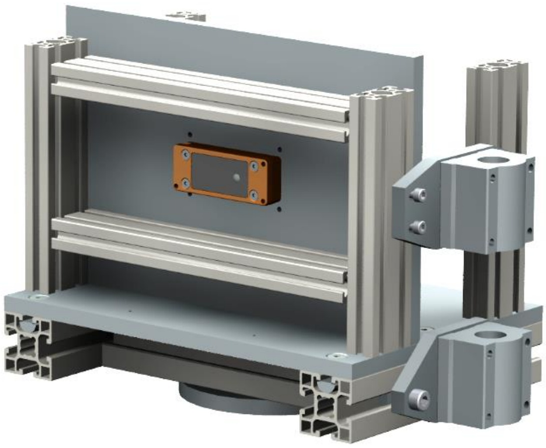

Figure 7.4, The accelerometer's standard mounting position on the back of the fixture plate.

The standard placement for the accelerometer is on the backside of the fixture plate. Assuming the specimen is normally mounted in the center of the fixture plate, then this become the ideal place as the certification standard dictates that the accelerometer should be placed as close as possible to the specimen's mounting points to get most accurate measurement of what acceleration the specimen actually experiences. This placement also means that it doesn't need to be moved when testing different orientations.

7.2 Programmer Dimensions

Initial work was focused around finding components made in Polyurethane (PU) or similar material which could be repurposed and function as a programmer, e.g. vibration dampeners for large machines etc. A similar approach as done during the concept test, although it was quickly deemed as less optimal for two reasons, the general lack of material data available and the lack of a conical top surface.

Basically all components of this type lack the material data necessary to be able to estimate what size of the component is needed since the commonly displayed Shore value can't be reliably transferred to Young's modulus (E) or rebound (α). Almost all components have a ±5 Shore A tolerance and the material properties will inevitably differ between the manufacturers as well. A reliable comparison between components can't be made without a physically testing them all.

The least time-consuming option in the long run, was to order a solid 1m PU-rod and then have it machined into several programmers of varying height. By ordering a range of sizes, the idea was to compensate for the variation material properties, the range of potential payload weights, the range in shock amplitude and the fact that equations used to calculate the programmer dimension describe an ideal case. Thereby one of the programmers should be able to produce the correct shock pulse.

As described by Lalanne *"it is undoubtably quicker to carry out a first test, to measure the values of $\hat{A}$ and D obtained, then correct k and v_i"* [5] due to the fact that the ideal case is calculated. However, as the minimum order dimension for the type of PU-rod needed was 1m and at a relatively high cost, ordering a second one after a first round of testing should preferably be avoid.

Equation (6.7) was used to calculate the programmers preferred dimensions based on the necessary spring constant in the same way as done in Chapter 6.6.

The following list of things have to be taken into considered when choosing the optimal combinations of hardness, diameter and the range of programmer heights to cover the widest range possible of programmer performance, centered around the ideal test case.

- The programmer height should not exceed the diameter, thereby should be lower than a 1:1 ratio [7]. Buckling might otherwise occur as seen in Chapter 6.6.
- The programmer height is also limited by that the compression distance should not exceed 10-15% of the programmer height. The materials spring constant will otherwise become non-linear [5].
- The hardness should preferably be ≥75A to be workable in a lathe.
- Higher Shore value equals lower rebound, thereby slightly less symmetrical pulse shape.
- To be able to regard it as a simple spring, it's necessary that the propagation of the shock wave through the programmer is weak which can be estimated to be true if Equation (7.1) is fulfilled [5].
- An increased diameter meant increased cost.

$$\frac{m_{payload}}{m_{prog.}} \gg \frac{4}{\pi^2} \approx 0.4 \tag{7.1}$$

A conical top surface is absolutely needed to avoid the shock wave resonance phenomena shown in Figure 6.20. Having a conical tip results in shock curve which is shape more as a versed-sine (or haversine) curve, see Figure 7.5. In short, the beginning and end of the shock curve have a more gradual transition and the tip should therefore not he too high.
No literature or publication were found which included any guide rules or equation for determine a suitable tip angle. An approximation based on images of other programmers where instead used.

Six programmers, with a tip angle of 156° and a height ranging from 45-95mm were made. A set of programmers with varying tip angle where not made as part of this initial order to reduce the initial cost until it had been verified whether or not the programmer worked as intended. A $0{,}5\ m$ long piece of the PU cylinder where left after the 6 programmers had been made. An updated version of the programmers could then be made from this by a local machine if the initial test results showed that this was necessary.

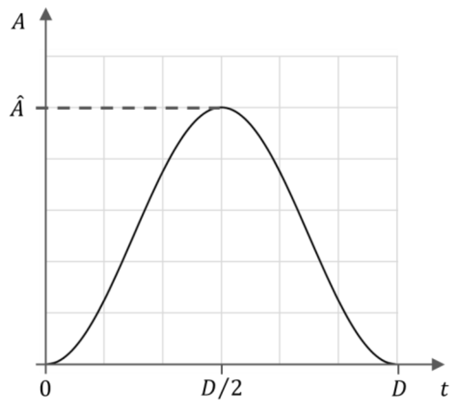

Figure 7.5 Versed-sine curve

7.3 Construction of the Shock Tester

The aluminum profiles were all pre-cut and drilled by the manufacturer, and the aluminum plates were made by a local machine shop. The only thing done at Verisure was to bolt all parts together. Figure 7.6 shows the finished STE. The programmer is fastened with double-sided tape.

Figure 7.6, Finished prototype build.

8 Initial Testing and Evaluation

An initial round of tests was done with the shock tester to evaluate its performance in relation to the target specifications and to determine what parts needs further work and what questions remains and need to be further tested. Due to the limited time of this thesis, only this round of initial tests was included. Apart from evaluating the current status of the shock tester, the purpose was to lay the ground for what needs to be done as this project is continued, after the thesis. The results of these tests are presented in this chapter.

The following things and questions were included this initial round of tests

- The structural durability of the frame and all parts. Especially those that were subjected to full force of the impact.
- How close to nominal 100 g pulse could it get?
    - Could test parameters be found which produced a pulse within the tolerance curves set by the certification standard [2]?
    - How well would these test results match the calculated values?
- How consistent are the pulse curves when performing several consecutive drops? I.e. evaluate the shock testers repeatability?
- With what precision can a shock curve’s peak amplitude be determined before-hand? Thereby how well does the calculated peak amplitude correlate with the measured one.
- How much and in what way, if any, does the measured shock pulse vary when the accelerometer (and specimen) is mounted on the three different fixture orientations.

8.1 Structural Durability and General Functionality

In the first tests, the main objective was to evaluate the structural durability of the whole machine as well as to evaluate its functionality overall. The drop height, and thereby the forces imparted on the machine, i.e. the peak amplitude, was increased in several steps. In between these, all parts were visually looked over and measurements were taken at key points to determine is anything moved, deformed or changed in any way. The tests reached a maximum drop height of 60 cm and close to 140 g. The payload, i.e. the table and fixture remained the same at 7.3 kg.

All tests were performed on the ground floor where the floor surface comprised of a concrete surface covered with a linoleum type mat. This flooring provided some added dampening, although minor. The accelerometer was placed in the middle of the table surface and fastened with double-sided tape, unless otherwise specified. The fixture plate was mounted to the table in the 90° orientation as shown in Figure 7.3b during all tests, unless otherwise specified. This was done to ensure that the weight of the whole carriage, table and fixture, were the same as it would be when test with a specimen. This general test setup is shown in Figure 8.1.

No permanent effects or changes to the frame, the table etc. were seen. No screws came loose and the movement of the carriage along the guide rods remained unaffected. The distance between the middle two beams of the lower frame and the floor where measured before and after, with no change. Thereby the lower frame seems to handle the forces without any deformation.

Lifting the carriage by hand and dropping were easily done. By standing to the side the of the machine the vertical aluminum profile of the frame helps to ensure that the user stays at a safe distance from the moving carriage. By then grabbing either the table corner of the top of the fixture with one hand only, the user could with relative ease and in a safe way lift and drop the carriage without risking that the carriage accidentally hits the legs, feet or hands as it falls and bounces.

It’s deemed safe enough to use with caution, although a lock and release mechanism should be added to increase the safety as well as ensuring that the carriage is dropped in a consistent way every time.

Figure 8.1 The general test setup, with the carriage in a raised position. (Note, the feet have been removed in this image as explained in Chapter 8.1.1 below)

8.1.1 Issue of STE moving at impact

A problem with the design was that the whole shock tester "jumped" straight up with each test. Approx. 1.5 cm, judging from the slow-motion video taken of the tests and when the peak amplitude was around 100 g. This was caused by the frame and rubber feet being compressed and then rebounding in combination with the relatively low weight of the STE (approx. 20 kg). This was an expected possibility and it was more prominent then what was hoped for. The alternative for solving this problem was either to increase the weight of the lower frame considerably by adding weights to the frame around where the feet are placed, or by removing the feet altogether and placing the frame straight on the floor. The second option was chosen as part of this initial round of tests as it was the simplest and least time consuming. This resulted in increasing the overall surface area of the STE as well as removing the frames ability to flex. Although the linoleum flooring still added some flex and dampening. The difference this had on the shock curve can be seen in Figure 8.2.

Both the amplitude and pulse duration changed. When examining them separately, the average peak amplitude and pulse duration, from 3 consecutive drops, were deduced. With the rubber feet the average was values were 5.5 ms and 110 g. Without the feet, both the pulse duration and the peak amplitude increased to 6 ms and 125 g. It's not evident why both the amplitude and duration are less when the feet are attached. Although, it's probably caused by some of the carriage's kinetic energy being transformed into the movement of the frame thereby reducing the velocity change of the carriage, i.e. the area under the curves.

The curve with the rubber feet is also less symmetrical and more "dragged out" at the end. This is most likely caused by the fact that the whole STE moved upwards with the carriage resulting in the carriage stays in contact with the programmer for longer before they separate, which is the moment when the measured acceleration equals zero.

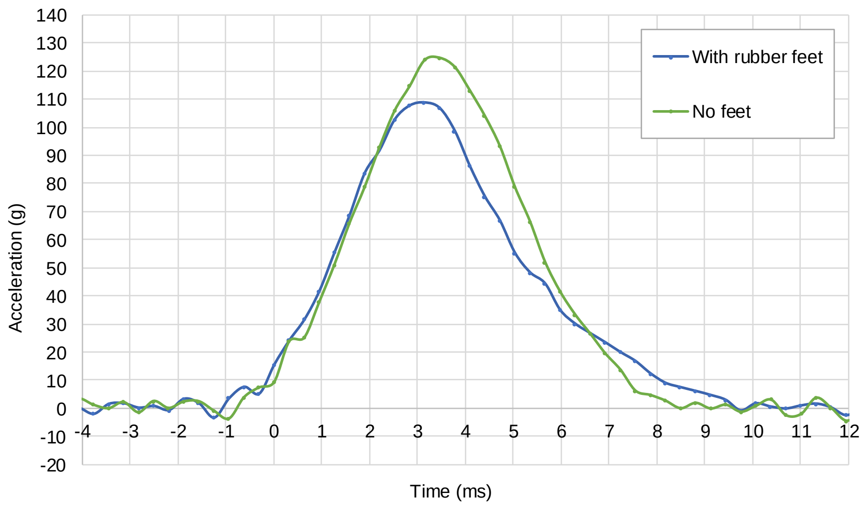

Figure 8.2 The effect that removing the rubber feet has on the shock pulse.

This dragged out shape is not desirable as it makes shock curve less symmetrical and takes it further from the nominal curve. The setup without the feet are the preferred option between the two. The STE still moved, or "jumped", a minute amount, although barely noticeable.

8.1.2 **Several impacts due to no brake mechanism**

As no brake mechanism had been implemented yet to either stop or slow down the carriage's movement after the first impact. The carriage bounces and impacts the programmer several times per drop, as can be seen in Figure 8.3. Both the second and third impact have a relatively high peak acceleration of 60 respectively 40% of the main impact. This might have a negative impact on whether the specimen passes the test or not and should be addressed later on.

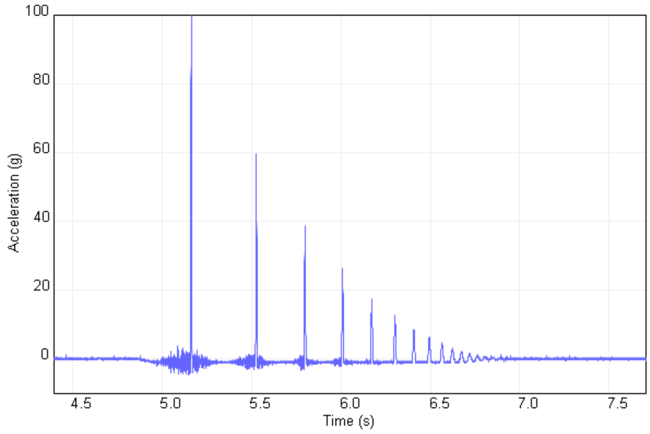

Figure 8.3 The measurement data from one drop. The carriage bounces and impacts the programmer several times. Each spike in acceleration is an impact.

8.1.3 **FFT analysis to investigate the risk of aliasing**

An FFT analysis (Fast Fourier Transform) was done on a short time interval around the main shock pulse. The measurement was done using a borrowed accelerometer with a higher sample rate to ensure that there weren't any resonance frequencies in the carriage which could have a negative effect on the main accelerometer's ability to measure the correct acceleration due to the aliasing phenomena.

The borrowed accelerometer was a Slam Stick X with a response range of 25g but a significantly higher sample rate of 20kHz. Due to the relatively low response range, the test had to be a low g-load test with a peak of 21g. Although this should still be sufficient to detect if there are any underlaying frequencies during the impact which might cause aliasing. The frequencies that might cause aliasing for the main accelerometer are equaled to half its sample rate, i.e. 1600Hz. The FFT results are shown in Figure 8.4 and since there are no frequencies of significant amplitude above a 100Hz, the conclusion is that there is not clear risk of aliasing. The result data from the main accelerometer can thereby be assumed trustworthy.

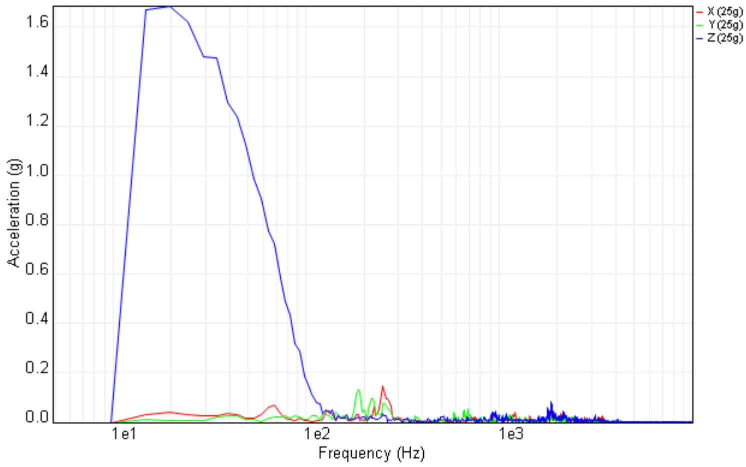

Figure 8.4 FFT analysis of a 0.2s time interval surrounding the main shock pulse

8.2 Nominal Curve and Repeatability

Different programmers and drop height were tested to empirically find the combination which gave the shock pulse closest to the nominal curve of 100 g and 6 ms. The best result was found using the lowest programmer in the range and with at a drop height of 30 cm. Three consecutive drops where made for every test setup, partly to measure the consistency of the STE and to average out any irregularities that might be present. The results from the three drops in this case are shown in Figure 8.5.

The shock curves have a peak amplitude deviation of less than ±1 g. Similar consistency of approx. ±1.5 g where seen in all the other tests as well, giving it a good repeatability. Although the shape along the top of the curve is not always as smooth and consistent in some test cases. This is most likely caused by the shock wave from the impact that travels through the frame and base plate and reverberates back up to the table. However, these irregularities seem at least to appear consistently in all 3 drops done as part of each test.

The shock pulse does for most parts stay within the tolerance limits for a 6 ms, 100 g pulse, as can be seen in Figure 8.5. However, the conical shaped top surface of the programmer causes the force applied to the carriage by the programmer to be more gradual in the beginning and end of the shock pulse. Thereby giving it a more versed-sine shape. The effect becomes more evident when comparing this shape to a more strict half-sine shaped pulse as seen during the concept testing, see Figure 6.18.

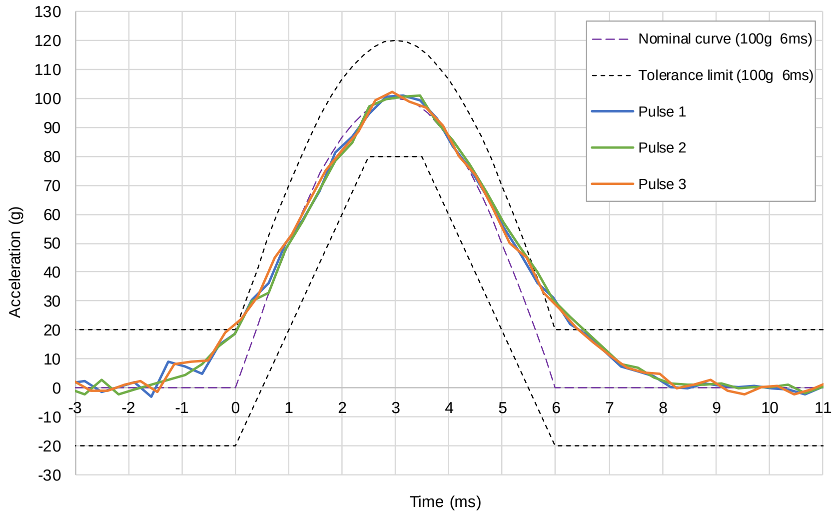

Figure 8.5 The resulting shock curves from three consecutive drops.

It's mainly this versed-sine effect which causes the curve to move away from the nominal curve in the beginning and the end of the shock pulse. The fact that the whole STE still moves slightly upwards after the impact is probably the main cause why the shock curve is more "dragged out" at the end than in the beginning. Adding these two effects together causes the pulse curve to stray outside the tolerance limits more clearly at around 6 ms mark in Figure 8.5 than at $t = 0$. This also causes the area under the curve to increase, thereby increasing the Δv of the shock. However, the Δv deviated only 14.1% from the nominal value, thereby still within the ±15% limit for a certification shock test.

Thereby if the angle of the programmer's conical top were decreased, much of this effect could probably be removed. If the weight of the STE were increased as well, making it more stable and planted to the floor, it should be possible to get the pulse curve within the tolerance limits.

8.2.1 **Cross-axis motion**

The sideways forces are minimal and well within the set maximum limit of 30% of the measured main direction, as defined by the certification standard [2]. The motion of the carriage seemed visually stable and sideways acceleration and was far below the 30% maximum limits.

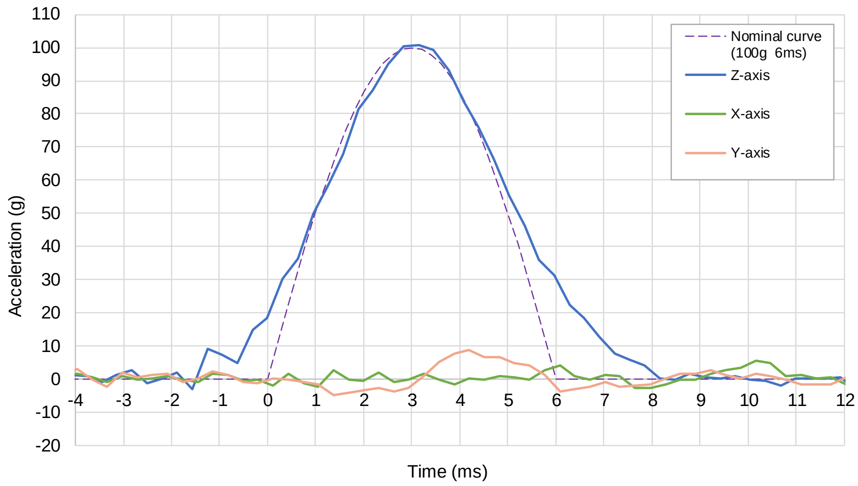

Figure 8.6 Sideways forces in comparison to the main test direction (Z-axis)

8.2.2 **Empirical compared to calculated test parameters**

The programmer used to produce the 6 ms pulse in Figure 8.5 were the smallest of the six programmers. This differed significantly from the calculation made in Chapter 7.2. The ideal programmer, based on the calculations, should be one of the two middle programmers in the range of six programmers made.

Several factors can be contributing to this, the relatively high conical tip, the manufacturers tolerance range ±3 Shore A and the fact that the ideal calculation made in Chapter 7.2 doesn’t include the materials dampening. But one factor alone can’t explain the entire difference.

Using the same equations and calculating what the Young’s modulus should be for the smallest programmer to be able to produce the measured shock pule gives it a value of almost half of what it should be.

The height of the conical tip equals approx. 15 mm which is more than 3 times the estimated compression distance of 4.7 mm needed to produce a 100 g pulse. From the slow-motion video taken of the impact, it seems to be mainly the conical top that is compressed. Although to what extent relative to the rest of the programmer is not possible to determine. The next step should therefore be to reduce the height of the conical top and test again to determine its contribution to the problem.

To be noted is that the drop height relative to peak amplitude agrees well with the calculations, as shown in the next chapter. Thereby the impact velocity is correct, and the problem lies with the programmer.

8.3 Amplitude Adjustability and Precision

As defined in the target specification, the shock tester should have the ability to adjust the amplitude both to accommodate specimens with different weights and to be able to vary the shock severity to find a specimen's breaking point.

The weight of Verisures product range vary approx. between 50-500 g. This result in a peak acceleration of 90-100 g according to Equation (3.1). To test this ability, the drop height for the three cases of 90, 95 and 100 g were calculated and tested. Assuming the ideal case, as previously discussed, the amplitude is only dependent on the drop height and the pulse duration should stay the same as long as the payload weight remains unchanged. Figure 8.7 shows the result from this and Table 8.1 show the difference in the calculated and measured amplitude.

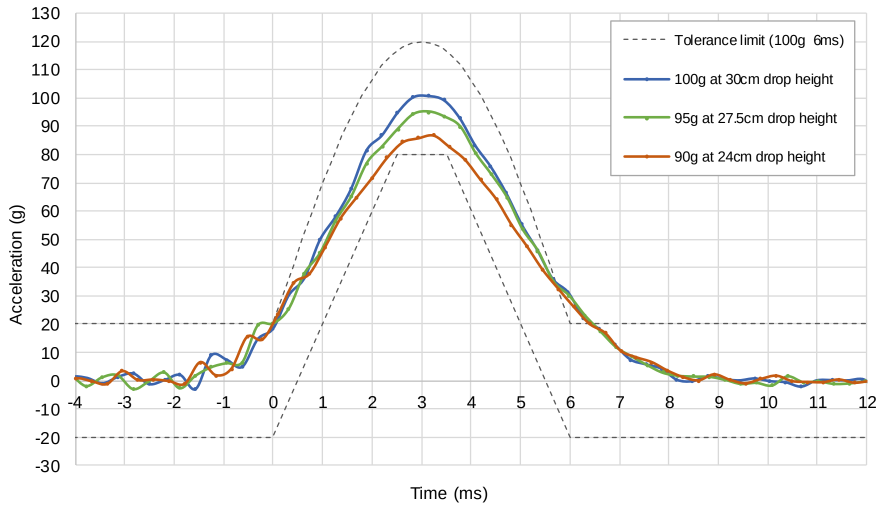

Figure 8.7 Drop height adjusted with the goal of achieving a shock curve with peak acceleration of 90, 95 and 100 g.

Table 8.1 Comparison between calculated and measured peak acceleration.

	Calculated peak acceleration (g)	*Drop height (cm)*	*Measured average Peak acceleration (g)*	*Estimated pulse duration from measurement (ms)*
1.	100	30	101.4	~6
2.	95	27.5	95.6	~6.1
3.	90	24	87.2	~6.2

The exact pulse duration is difficult to measure as the shock pulse's versed-sine shape have the effect that only the middle part of the curve can be used when attempting to find what values the nominal curve should have when matching it with the measured pulse curve.

There are some differences between the measure and the calculated peak amplitudes as shown in Table 8.1. This equation could with further testing be replaced by empirical data to increase the precision when setting up the STE before a test and increase the likelihood of hitting the intended peak acceleration.

8.4 Testing all Fixture Orientations

The fixture plate can be mounted in three different orientations, 0°, 90° and 180° as shown in Figure 7.3. The shock curve, as experienced by the specimen, should be within tolerances for all these 3 cases. The accelerometer is in these cases mounted to the backside of the fixture plate as shown in Figure 7.4.

Figure 8.8 shows the pulse curves for these 3 cases. Both the 0° and 90° orientation have a more or less identical shock pulse. The shock curve for the 180° fixture differ only at the very peak, although it's still within the tolerance limits.

The theory behind this increased amplitude at the peak of the curve, while the programmer is most compressed, is that the suspended fixture plate flexes and resonates in its natural frequency, thereby boosting the shock pulse at that moment. The natural frequency of the metal fixture plate is likely too high for the accelerometer to measure in sufficient detail which result in the pulse curves being so irregular at the top. Figure 8.9 show all 3 shock pulses from testing the 180° fixture and all shock pulses show similar irregularities at the top.

Thereby, the beams on the backside of the fixture plate are not sufficient to stiffen up the fixture and hindering it from flexing.

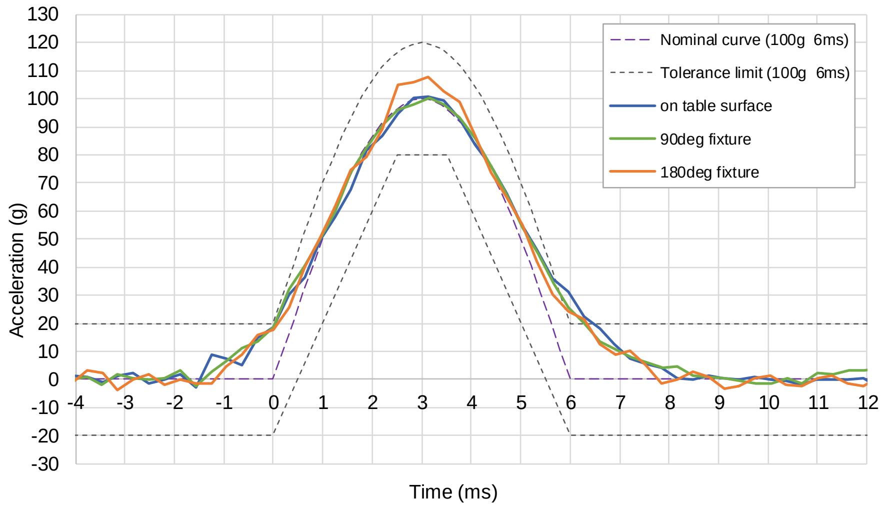

Figure 8.8 The difference in perceived shock depending on how the fixture plate is mounted.

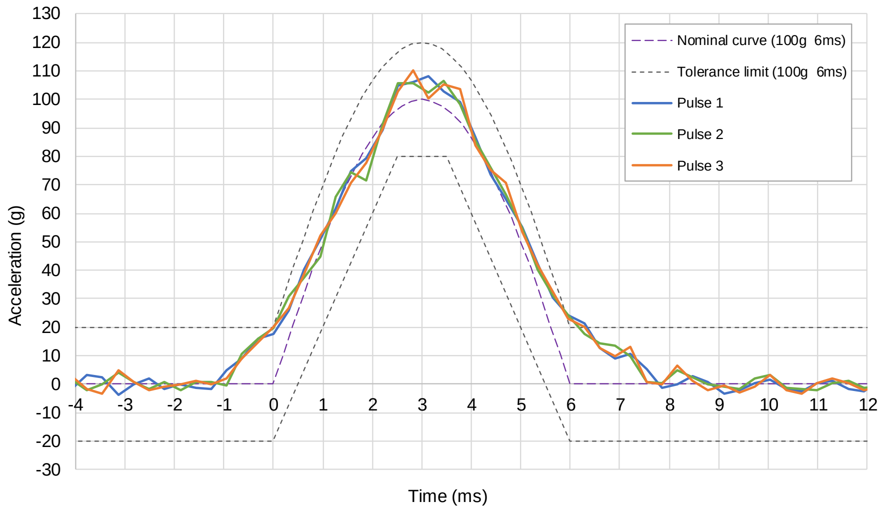

Figure 8.9 The 3 shock pulses when testing the 180deg fixture.

9 Conclusion

Conclusions made based on the shock tester's initial performance as well as conclusions made about the overall product development process are presented in this chapter.

The main conclusion drawn from the initial testing of the shock tester is that the STE works, and it fulfills all target specifications to either the Acceptable or Ideal level. Table 9.1 on page 88 shows an overview of to what degree the different target specifications were achieved. The target specifications for the accelerometer were not shown in a similar way as it has already been discussed in Chapter 5. As a first prototype and a platform to continue to build on, the work was successful.

The shock pulses produced are almost completely within the half-sine tolerance limits set by certification standard. Although this fulfills the Acceptable criteria, it should be possible to further increase the performance with a relatively small amount of work. Thereby moving the shock pulse closer to the nominal curve and getting even closer to what the products will be subjected to during the certification test.

The need for a heavy base was underestimated in the search for a simplified and lightweight construction which resulted in that the Shock tester "jumping" approx. 1.5 cm straight up as the frame and rubber feet were compressed at impact.

The used solution of removing the feet and placing the frame directly on the floor works and helped to remove most of the "dragged out" shape that the shock curve got due to whole shock tester jumping. However, in the end, the optimal solution would probably be to use the feet and instead increase the weight of the whole shock tester. This since the shock curves got slightly more "wobbly" when placed directly on the floor which is most likely caused by the shock wave from the impact that resonates back and forth through the frame and up to the table.

The combination of using aluminum profiles and plates proved to be a sufficient solution in creating both a stiff enough table and a stable frame. This is evident by the fact that even though the shock curves aren't as smooth as hoped for, they are highly consistent with a peak acceleration variation of approx. ±1g.

The idea of using a single fixture plate for all test orientations seems so far to be good solutions although a final conclusion will have to wait until tests with a specimen mounted to fixture have been done. Some irregular motion was present when testing with the fixture plate mounted in the 180° orientation, see Figure 8.9. This should be further evaluated while different specimens are mounted to it, but in the end, the plate might need further reinforcement to counteract this motion.

The carriage impacts the programmer several times for each drop, as shown in Figure 8.3. The amplitude of both the 2nd and 3rd impact equals approx. 60 and 40% of the first impact. This could have a decisive effect whether a specimen pass the test or not considering that every specimen shall be dropped 18 times in total, 3 times in each of the 6 orientation. Some type of brake system is therefore necessary to avoid these secondary impacts.

The development process used in this thesis worked well overall. Although the need for clear delimitations when designing a product with few design restrictions became very evident. Dividing the concept generation into several steps, first making more general design decision to further delimiting the design and then dividing into several subproblems was essential to limit the amount of possible designs and to reaching the end goal within the given time frame.

Although the accelerometer is sufficient while the STE works as intended, the performance might be hindering the ability to correctly diagnose the cause when a problem occurs. It would have been a wiser choice to have purchased a more expensive model with a higher sample rate to ensure that it has sufficient resolution to catch any unpredictable behavior. This became evident both when testing with a flat programmer, see Figure 6.19 and when testing with the fixture plate mounted in the 180° orientation, see Figure 8.9.

Table 9.1 The achieved target specifications for the shock tester and to what level.

Primary needs		***Ideal***	***Acceptable***
1.	**Produce a half sine wave pulse**	Within ±20% of nominal curve ✓	Within ±30% of nominal curve
2.	**Velocity change deviation from nominal pulse**	±15% ✓	±25%
3.	**Cross-axis motion** ~~**and secondary impacts**~~	±30% ✓	±40%
4.	**Repeatability**	±5% ✓	±10%
5.	**Adjustable pulse amplitude (g-force)**	40-140 g (5 g/step) ✓	90-110 g (10 g/step)
6.	**Main amplitude step (g-force)**	85, 90, 95, 100, 110 g ✓	90, 100 g
7.	**Weight of the specimens**	≤2 kg	≤1 kg ✓
8.	**Maximum specimen dimension** (LxWxH)	-	Specimen 240x170x150 mm ✓
9.	**Specimen mounting orientation**	-	All 6 directions. ±X, ±Y, ±Z ✓
10.	**Mounting hole configuration**	Nonspecific. ✓	Grid structured holes
11.	**Safe to use**		Risk assessment ✓
Secondary needs			
12.	**Easy to use**	Plug & play. Intuitive functionality ✓	Written instructions needed.
13.	**Moveable. Can be stored elsewhere when not in use**	Can be carried in small parts. ✓	Wheeled or with a trolley
14.	**Max. weight, Total**	20 kg	100 kg ✓
15.	**Max. weight, of each part when carried**	5 kg	20 kg ✓
16.	**Max. weight, of each part when wheeled**	~~15 kg~~	~~50 kg~~
17.	**Max. dimensions Operational**	0.5x0.5x1 m ✓	1x1x2 m
18.	**Max. dimensions Stored**	0.5x0.5x0.5 m	1x0.7x1.5 m ✓
19.	**Minimal maintenance.**	None	Assessment with HW team ✓
20.	**Power source**	None ✓	Standard wall outlet.
21.	**Overall cost**	≤20.000 SEK	≤40.000 SEK ✓

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Appendix A

Table 0.1 shows the dimensions and weights for some of Verisures products. The products displayed were chosen to include those which were at end of the range in respect to weight and size. This is used to get an estimate of the range of dimensions which the shock tester needs to accommodate. A few other products were also included as reference to the first ones.

Table 0.2 shows the dimensions for a few products from other companies which might be relevant in the future and which are comparatively large and heavy.

The products which are the largest and heaviest, are marked in red.

Table 0.1, Dimensions and weight of various Verisure products.

Verisure products	***Weight*** *(gram)*	***Length*** *(mm)*	***Width*** *(mm)*	***Height*** *(mm)*
Product SA	44	88	24	15
Product SB	385	172	102	31
Product SC	557	190	125	70
Product SD	176	42	61	140
Product SE	141	100	100	35
Product SF	177	150	86	32
Product SG	200	59	59	68
Product EA	364	240	125	35
Product EB	414	120	120	70
Product EC	220	120	120	45
Product ED	543	95	95	130
Product EE	503	195	78	30
Product EF	590	182	84	86
Product EG	420	100	100	145

Table 0.2, Dimensions and weight of various, relevant competitor products.

Competitor products	***Weight*** *(gram)*	***Length*** *(mm)*	***Width*** *(mm)*	***Height*** *(mm)*
Product CA	820	88	88	148
Product CB	1760	246	174	107
Product CC	480	96	96	143
Product CD	480	178	118	67

Appendix B

Table 0.3 and Table 0.4 shows the benchmarking made of the commercially available shock-testing machines. No comparative scoring was made between them, as none fulfilled all necessary requirement. The information given for each machine is in many cases incomplete due to the information available up front varied a lot and it often wasn't necessary to fill in all fields to make a sufficiently informed judgement.

Table 0.3, Market evaluation

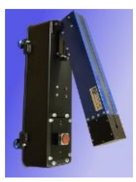
			
Modell:	SD-10	STM10P	STM5
Företag:	L.A.B equipment	L.A.B equipment	Elstar (L.A.B equipment)
Länkar:	Produkthemsida	Produkthemsida	Produkthemsida
Pris:	*462.000 kr (50 000 USD)*	*580.000 kr (63 200 CHF)*	*490.000 kr + air pressure sys. (53 000 CHF)*
Leveranstid:			
Type:	Drop tower	Pneumatic	Pneumatic ram
Max g-load:	3500g	20-140g (ish) @6ms (up to 1400g)	2000g
(Min) Pulse duration:	0.3ms	0.5ms	0.3ms
Max velocity change:		5m/s	5 m/s
Max. payload: (Specimen + fixture)	14kg	10 kg	5kg
Table size:	254 x 254 mm	320 x 250mm	152 x 152 x 152 mm mounting surface
Programmer type:	HS, Trap		?
Automated drop cycles:	Yes		Yes, 1/sec
Power source:	Wall outlet	Pressurized air 4-8 bar & Wall outlet	Pressurized air 4-8 bar & Wall outlet
Mounting hole pattern:	M6x1, 50mm grid		
Floor space required:	0.3 x 0.65 m	0.45 x 0.37 m	0.4 x 1.3 m
Height:	2.4m	0.95m	
Weight:	430 kg	440 kg	120 kg
Dimensions:		400 x 320 x 800-950mm	350 x 1250 x 1070mm
Carriage weight:	20kg		

Table 0.4, Market evaluation continuation

							
PST-300	PDST - 230M	Model 23D	ASLi SS-10	MS200	STM10	1010-100	ACST-200
Shinyei	Shinyei	Lansmont	ASLi (China)	ETS solution (China)	L.A.B equipment	M/RAD corp	Yoshida Seiki (China)
Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida
	"Pull down shock tester	liknande modeller		(all products)			Produkthemsida
450 000kr *(48 000 USD)*			330 000 kr (35 000 USD)		*500.000 kr* *(54 800 CHF)*		*inspiration från bild endast*
			10 veckor				
Pendulum	Pull-down drop tower	Drop tower	drop tower	drop tower	Pneumatic	Free Fall	
5 - 5000G	50-800g	2000g			5-40g @6ms (up to 500g)		
0.2 / 0.5 / 1 / 6 / 11 ms	2.5-20ms	> 0.2ms				> 0.5ms	
	Up to 15m/s	7.3 – 9.7 m/s maximum			2.5m/s	max impact velocity 5m/s	
0.8 kg	20kg	18kg	10 kg	10 kg	10 kg	45 kg	?.3 kg - 10.0 kg
100 mm diameter	?36 × 236 mm	150 x 230 x 230 mm	200 x 200 mm	200 x 200 mm	320x250mm	250 x 250 mm	220 x 220 mm
HS	HS	HS, Trap, Saw	HS, Trap, Saw	HS, Trap, Saw			
	Yes				Yes, 1/s	Y	
AC100V, 1A	Wall outlet Air supply: >0.8MPa and 350dm³	240V 6.2bar air		... hyrdralic pump	Pressurized air 4-8 bar & Wall outlet	240V. Pressurized air or bottled nitrogen 80-120 psi	3-phases
	0.65 x 0.8 m	0.5 x 0.6 m			0.45 x 0.37	0.7 x 0.7 m	
	1.8m	2.4 - 3 m		2.6m	0.77 m		
100 kg	1500 kg		700 kg	1000 kg	320 kg		480 kg
620 × 360 × 675 mm	W650 × D800 × H1800mm			770 x 680 x 2570 mm	400 x 320 x 620-770mm		W565 x D740 x H2730
						12 kg (25lb)	

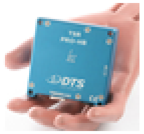
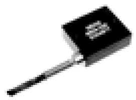
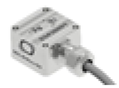
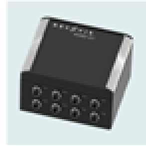
Appendix C

Table 0.5 and Table 0.6 shows the benchmarking made of the potential accelerometers. No comparative scoring was made between them, selection was made through discussion and using the parameter listed in these tables.

Table 0.5 Accelerometer benchmarking

				
Modell:	Slam Stick C	Slam Stick X	Slam Stick S	AccStick
Företag:	Mide	Mide	Mide	Shinyei
Länkar:	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida
	Slam Stick Overview page			
Pris:	9300kr (1.000 USD) + importskatt och frakt	14 000kr (1500USD) (Metal 18 600kr (2000USD))	28 000kr (3000USD)	14 000kr (1500USD)
Leveranstid:	2 veckor			
Sensor type: (PE,PR,MEMS)	MEMS	PE + MEMS	PR + MEMS	MEMS
Logger or cabled:	logger	logger	logger	logger
Nbr of axis:	3axis	3axis	3axis	3axis
Dynamic Range (g's):	±200g	±500 g	±500 g	± 100, 200, 400g
Sampling rate:	3.2 kHz	100 - 20 kHz	100 - 20 kHz	800Hz (vib. sensor m 1600Hz)
Frequency Response (Hz): Bandwidth	X & Y: 0 - 1,000 Hz Z: 0 - 500 Hz	5 - 2,000 Hz (plastic case)	0 - 2,000 Hz	???
Data Resolution (bits):	13 bit (12 bit, sample > 16	16-bit	16-bit	?
Lowpass filter type: (Anti-Alias filter)	2nd Order filter	5th Order Hardware Butterworth	5th Order Hardware Bes	?
Low Frequency Cut-off:	1/2 Sample Frequency			?
Noise level:	< 0.14 g RMS	< 0.20 g RMS	< 0.40 g RMS	
Resonance freq:				
Size LxWxH:	76 x 30 x 15 mm	76 x 30 x 15 mm	76 x 30 x 15 mm	33 x 21 x 11 mm
Weight:	40g	40g (65g)	65g	15g
Memory:	1Gb (=16h data)	2Gb	2Gb	4MB, max 500k data poi
Battery:	14.5h			Li-Po rechargeable battery
other sensors incl:	pressure, temp	pressure, temp	pressure, temp	Vib. & shock sensor
Connection to PC:	USB	USB	USB	USB
Software:	Free software Slamstick Lab	Free software Slamstick Lab	Free software Slam stick lab	Inkluderat

Table 0.6 Continuation of accelerometer benchmarking

							
TSR Pro	Saver 3x90	RecoVib Tiny	3700	4604	USB4431	RecoVib IAC	Recovib Mimd
DTS	Lansmont	Micromega	Swe automatik	Swe automatik	NI, National Instrumen	Micromega	Micromega
Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida	Produkthemsida		Produkthemsida	
Distributör					preliminär kostnad		
					USB 4431 - 27 700kr		37 000kr
75 000 kr	ca 85 000kr	11 700kr			CompactDAQ + mod.	14 000kr	(3550€) Cheaper ver. is
(old quote)	(€ 8.100,00 old quote)	(1.125,00 €) + frakt		7 000kr	9300kr	(1342€)	coming soon. "Much
				8-10veckor			
MEMS	PE	MEMS	PR MEMS	MEMS			
logger	logger	logger Wireless	cable	cable		cable	
tri-axial	tri-axial	3axis		1 (antar jag)		1 axis	
250g	200g	± 200G	± 200g (± 50 - 6000g)	± 200g		± 200G	
1k-20k samples/sec	5000Hz	1 KHz	Beror på övrig utrustning?			N/A	16 kHz per channel 8-channels
DC to 300Hz (DC to 1650Hz for PRO-	???	250 Hz	0 - 1500Hz (± 1/2dB) 0 - 1900Hz (± 1dB)	0 - 2700 Hz		0 - 3000 Hz	
16-bit	16-bit	?				N/A	24-bit
"4-pole Butterworth"	low-pass Butterworth filter. 4-pole	2nd Order filter (korrekt?)				2nd Order filter	
	... 200, 250 and 500 Hz					typ 1/2 sample_F	
		2600 µg/√Hz RMS, 47mg	<10 µV RMS	500 µV RMS		200 µg/√Hz RMS	
			8000 Hz				
72x 72x 22mm	95x 74x 43mm	40x 33x ? Mm	14 x 7x 4mm	25 x 22 x 8mm			
237g	473g	34g	2.1g	10g		100g	
nts		2Gb					
Lithium Flera olika varianter	2at 9V-batteries, continuous operation up to 90 days	6h					
	temp, humidity						
USB	USB						
Egen mjukvara TSR Control	Egen mjukvara SaverXware	Andriod och PC mjukvara igår				Spec. PDF Output Volt	Inkluderat