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**Development of a handle for an automotive battery
due to supply issues**

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Contents

List of Figures	6
List of Tables	8
1.0 Abstract	9
2.0 Introduction	10
2.1 Design of Handle	10
2.2 Company Backgrounds	11
2.2.1 EnerSys	11
2.2.2 Customer - Daimler	11
2.2.3 Supplier – Rope and Plastics	12
2.3 Project brief	13
2.4 Project Aim	14
2.5 Project Objectives	14
2.6 Product Application	15
3.0 Project Plan	17
3.1 Team Structure	19
3.2 Work Completed by Each Party	19
4.0 Methodology – Testing Method and Standards	20
4.1 Test Method Background Information - Relevant Standards	20
4.2 Continuous Load Testing	21
4.3 Force Calculations for minimum acceptable requirement - Continuous Load test	22
4.4 Derivation of horizontal load shown in Section 4.3	23
4.4.1 Test Results Summary	23
4.5 Derivation of Horizontal Load – Trigonometry method	24
4.5.1 Difference in Results	25
4.6 Sudden Loading Test Method	26
4.7 Force Calculations for minimum acceptable requirement - Sudden loading test	27
4.7.1 Reasoning why stress is doubled during sudden application of load	28
4.7.2 Reason for testing at different temperatures	29
4.8 EnerSys Testing Requirement	30
4.9 Current EnerSys Standard	31
4.10 Summary of this section	31
5.0 Methodology - Comparison of Testing Methods between EnerSys France and Supplier	32
5.1 Supplier Test Method	32
5.1.1 Supplier Test Method Results (5 samples) for reference	34
5.2 EnerSys Test Method	35
5.3 New Proposed Test Method by EnerSys Newport	36
5.4 Reasoning/benefits of Test method alignment	36
6.0 Methodology - New Proposed Test Method by EnerSys Newport	37

Contents

7.0 Results and Analysis after test method alignment	40
7.1 Supplier Test Results – For Reference	40
7.2 Comparison of EnerSys and Supplier results post-test method alignment	41
7.3 Distribution of EnerSys Results - Results comparison with previous batch	42
7.3.1 Currently Supplied Handles	42
7.3.2 Previously Supplied Handles	42
7.4 EnerSys Results - Results comparison with previous batch	43
8.0 Methodology - EnerSys Newport Testing (Factor of safety of 3 physical test)	45
8.1 Test Method	45
9.0 Results and Analysis - EnerSys Newport Testing (Factor of safety of 3 physical test)	46
9.1 Test Results of Currently Supplied samples (currently supplied handles)	46
9.2 Failure modes	47
9.3 Test Results of Previously Supplied samples (previously supplied handles)	48
10.0 Methodology - Root Cause Analysis	49
10.1 Main possible Contributors to Overmoulding from Research	50
10.2 Meeting Takeaway	50
11.0 Results and Analysis - Root Cause - Comparison of Rope Thickness	51
11.1 Thickness of Old Rope	51
11.2 Thickness and quality of New Rope	51
11.3 Exposed Strands	52
12.0 Results and Analysis - Root Cause - Thickness at Grooves Comparison	53
12.1 Originally supplied Handles (old rope)	53
12.2 Currently Supplied Handles (new rope)	53
13.0 Results and Analysis - Root Cause - Stress Analysis of End Moulding Sections	54
14.0 Design Constraints	55
15.0 Quality Control Document	56
15.1 Reasons for choosing this method of quality control	57
15.2 40% requirement of quality criteria document	58
16.0 Recommended actions based on Results and Analysis performed in previous sections Sept-22	60
16.1 Set the load requirements for the Handle as follows	60
16.2 Deviation for Batch of 40,000 supplied Handles with following conditions	60
16.3 Instructions for Rope & Plastics (supplier)	60
17.0 Results and Analysis - Screening Method performed at EnerSys	61
18.0 Results and Analysis - Screening at supplier non-compliance issue	62
19.0 Results and Analysis - Validation of Screening Method	64
20.0 Project objectives as of December 2022	65
20.1 Current actions after meeting 02/12/22	65
20.2 January 2023 – April 2023	65

Contents

21.0 Methodology - Structural Analysis of LER Prototype Design	66
21.1 Split	66
21.1.1 Advantages of Second order elements	66
21.1.2 Disadvantages of second order elements	66
21.2 Interpret	67
21.3 Material Properties	67
21.4 Physical Properties	69
21.5 Loading	69
21.6 Evaluation	69
21.7 General Views of Prototype Design	70
21.8 FEA Load case	71
21.9 FEA Constraint	72
22.0 FEA Results and Analysis	73
22.1 Results for production material - Polypropylene	73
22.2 Results for prototype material - Duraform ProX	74
22.3 FEA Evaluation	75
23.0 Methodology - Physical Experiment to compare with FE Model	77
23.1 Set-Up / Method	77
24.0 Results - Physical Experiment to compare with FE Model	78
25.0 Analysis - Comparison of results between FEA model and physical experiment	79
25.1 Reasons for differences in results	79
25.2 Suggested steps forward	79
26.0 Discussion	80
27.0 Conclusions	80
28.0 Further Works	81
28.1 Potential improvements to LER prototype design	81
28.2 Altering the thin section to be flush with the top surface of the handle	81
28.3 Increasing the thickness of the thin section	82
28.4 Alternative Rope Suppliers for the Current Handle Supplier	82
28.5 Summary of Next Steps	83
28.5.1 Short-term	83
28.5.2 Mid-Term	83
28.5.3 Long-Term and Project Importance	83
29.0 Works Cited	84
Appendix A - Raw Data	90

List of Figures

Figure 1 End Moulding and Cavity Assembly for Locking Mechanism	10
Figure 2 Full Handle Assembly outside of a Battery	10
Figure 3 Handle Assembled into a Battery	10
Figure 4 Daimler Battery (BatteryGuys, 2021).....	10
Figure 5 EnerSys SBS Battery Product Family (EnerSys 2011)	11
Figure 6 Mercedes Actros Truck (sparshattgroup, 2019)	11
Figure 7 Typical Battery Energy for Daimler Trucks (Mercedes-Benz Group, 2021)	16
Figure 8 Team Structure Diagram	19
Figure 9 Daimler Specification for Handle Strength Test (Daimler, 2020).....	21
Figure 10 EN 50342-5 Specification for Continuous Load Test (EuropeanStandards, 2010).....	21
Figure 11 Force Calculations for Continuous Load Test based on minimum requirement	22
Figure 12 Test Set-up for verifying calculated Horizontal Load	23
Figure 13 Rope dimensions in horizontal and vertical direction and resultant angle calculation.....	24
Figure 14 Comparison of Physical Testing Results and Hand Calculations	24
Figure 15 Daimler Specification Sudden Load Test (Daimler, 2020).....	26
Figure 16 EN 50342-5 Specification Sudden Load Test (EuropeanStandards, 2010).....	26
Figure 17 Force Calculations for Sudden Load Test.....	27
Figure 18 Force Calculations for Continuous Load Test Following EnerSys' requirement	30
Figure 19 Supplier (Rope and Plastics) Test Set-Up for Continuous Load Test.....	32
Figure 20 Comparison of Rope angle between supplier Test Set-up and battery installation.....	33
Figure 21 Small Sample Size of Supplier results for the continuous load test (tested to a factor of safety of 3)	34
Figure 22 EnerSys France Test Set-Up	35
Figure 23 Handle Installed into a Daimler Battery.....	35
Figure 24 Images Supplier took of failure modes of samples that have undergone the locking mechanism test.....	40
Figure 25 Boxplot comparing results between EnerSys France and Supplier for new Locking Mechanism Strength Test	41
Figure 26 Statistical Analysis of Difference in Results between EnerSys France and Supplier.....	41
Figure 27 Locking Mechanism Test - Distribution of Results for New Rope.....	42
Figure 28 Locking Mechanism Test - Distribution of Results for Old Rope.....	42
Figure 29 Histogram - Comparison of Results between New Rope and Old Rope for Locking Mechanism Strength Test	43
Figure 30 Capability Study of Locking Mechanism Test Results for the currently supplied handle	44
Figure 31 Capability Study of Locking Mechanism Test Results for the previously supplied handles..	44
Figure 32 Newport Physical Testing of Factor of Safety of 3 Test Set-Up	45
Figure 33 Newport Physical Testing of Factor of Safety of 3 Test Results for New Rope (5.5mm Diameter)	46
Figure 34 Sample 1 - Failure Mode 1 - Newport Physical Testing	47
Figure 35 Sample 6 - Failure Mode 2 - Newport Physical Testing	47
Figure 36 Sample 6 image prior to physical testing.....	47
Figure 37 Newport Physical Testing of Factor of Safety of 3 Test Results for Old Rope (5.0mm Diameter)	48

List of Figures

Figure 38 Fishbone Diagram of potential causes of Overmoulding Issue.....	49
Figure 39 Measurements of Rope Diameter (old rope).....	51
Figure 40 Measurements of Rope Diameter (new rope).....	51
Figure 41 Image showing Overmoulding Issue at end moulding (new rope).....	52
Figure 42 Diameter at Slots of End Moulding (Old Rope).....	53
Figure 43 Diameter at Slots of End Moulding (New Rope).....	53
Figure 44 Stress Calculations at each end moulding section.....	54
Figure 45 Assembly of Handle into Battery frontal view	55
Figure 46 Quality Control Criteria	56
Figure 47 Example of use of exposed strand criteria for a rope used on another product type (Historical Criteria) (EnerSys, 2016)	59
Figure 48 Initial Screening Details (performed at EnerSys France)	61
Figure 49 Screening Costs	61
Figure 50 Example of 'Bad Samples' picked out after supplier screening during EnerSys screening...	62
Figure 51 Capability Study of Locking Mechanism Test Results for the New Rope (5.5mm Diameter Rope) Post Screening to EnerSys Quality Criteria	64
Figure 52 Material Properties for PB150G2M Polypropylene received via email from a representative of Repsol (material supplier) (Reyes, 2023).....	67
Figure 53 Material Properties for PB150G2M Polypropylene (Repsol, 2021)	67
Figure 54 Material Properties for Prototype Material (secondary source) (Lindberg, 2018).....	68
Figure 55 Material Properties from prototype material supplier (3dsystems, 2016)	68
Figure 56 General View of Handle Prototype Design	70
Figure 57 Horizontal Load Case.....	71
Figure 58 Vertical Load Case	71
Figure 59 FEA Constraint.....	72
Figure 60 Deformation for Production Material.....	73
Figure 61 Stress values at Section 1 for Production Material.....	73
Figure 62 Stress values at Section 2 for Production Material.....	73
Figure 63 Deformation for Prototype Material	74
Figure 64 Stress values at Section 1 for Prototype Material	74
Figure 65 Stress values at Section 2 for Prototype Material	74
Figure 66 Model of Hand produced by the University of California (Yan, 2012).....	76
Figure 67 Prototype Handle Physical Test Set-up.....	77
Figure 68 Prototype Sample Failure Mode Following Physical Test	78
Figure 69 Thin section Modification to be flush with the top surface.....	81
Figure 70 Figure 62 Modification + Increasing thickness of section to 5mm	82
Figure 71 Figure 62 Modification + Increasing thickness of section to 8.5mm	82
Figure 72 Raw data for Testing performed at EnerSys France comparing the currently supplied handle (new) and previously supplied handle (current) ignore incorrect labelling	90

List of Tables

Table 1 Project Plan	17
Table 2 Rope Strength Test Procedure	38
Table 3 Locking Mechanism Test / Continuous Load Test Procedure	39
Table 4 Example of use of exposed strand criteria for a rope used on another product type (Historical Criteria) (EnerSys, 2016)	58
Table 5 Screening Data of Samples that conform to EnerSys Quality control criteria after being screened initially by the supplier then checked again at EnerSys	62
Table 6 FEA Load Case.....	71
Table 7 FEA Results for Production Material	73
Table 8 FEA Results for Prototype Material.....	74
Table 9 Rope and Plastics locking mechanism test results post-test method alignment.....	91
Table 10 EnerSys France locking mechanism test results post-test method alignment	92
Table 11 Horizontal Load Derivation - Testing Results	93

1.0 Abstract

Following routine testing performed at EnerSys France, it was found that the latest batch of Daimler battery handles supplied had a lower strength than what had been previously supplied and was performing to a factor of safety of 2.77 minimum at the locking mechanism. The root cause was determined to be a change in supplier for the rope used in the handle assembly; the current supplier (Rope and Plastics) advised that this was due to supply issues. EnerSys implemented a quality control procedure which involves 100% screening samples following visual inspection criteria. This procedure improved the strength of the handle locking mechanism, which now meets a safety factor greater than three. However, it is a costly process as both EnerSys and the supplier screen the samples due to the supplier having issues with screening correctly. Due to the project being put on hold, no long-term solution is currently implemented. However, results from physical testing of an alternative handle design from LER (an alternative supplier located in France) and results from two alternative rope suppliers for our current handle supplier (Rope and Plastics) show promising results as a replacement. Further work must be performed to ensure that these long-term solutions are fit for purpose.

Key Words

SBS – Smart Battery System

AGM – Absorbent glass mat

FOS – Factor of Safety

EN – European Standards

PPAP – Production part approval process

CPK - Process Capability Index

PPK - Process Performance Index

FEA – Finite element analysis

FE – Finite element

AQL - Acceptance Quality Limit

SPC – Single point constraint

NC – Not Conform

C - Conform

2.0 Introduction

2.1 Design of the Handle

In order to understand the function of the component considered in this project, the assembly must be understood. Figures 1 to 4 show the assembly of the handle which is the main subject of this project. These handles are installed in batteries that will be used in electric trucks; they are lifting aids to assist in installing the battery into the truck (additional information on product application is located further in this section). The product is failing at the locking mechanism at a lower factor of safety than was previously supplied.

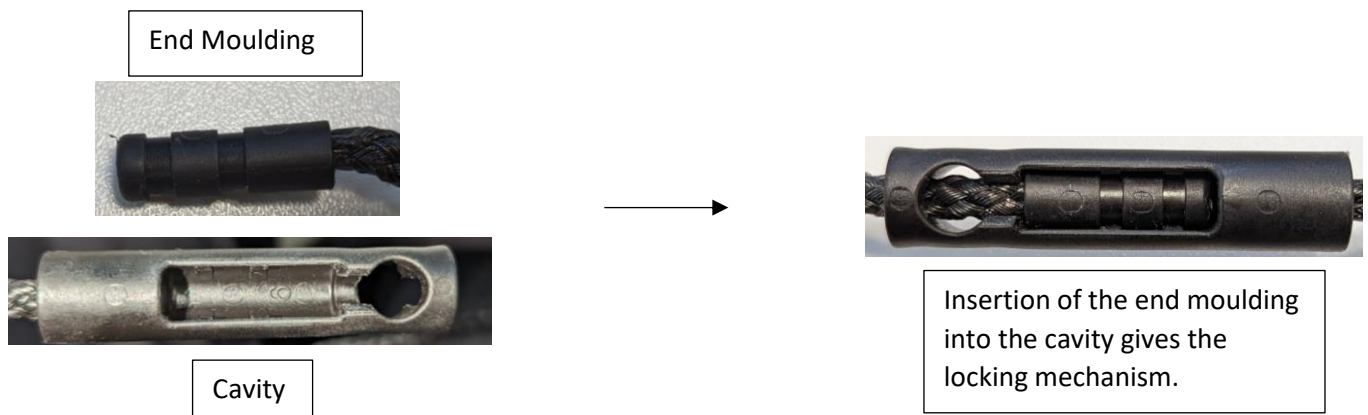


Figure 1 End Moulding and Cavity Assembly for Locking Mechanism



Figure 2 Full Handle Assembly outside of a Battery



Figure 4 Daimler Battery (BatteryGuys, 2021)

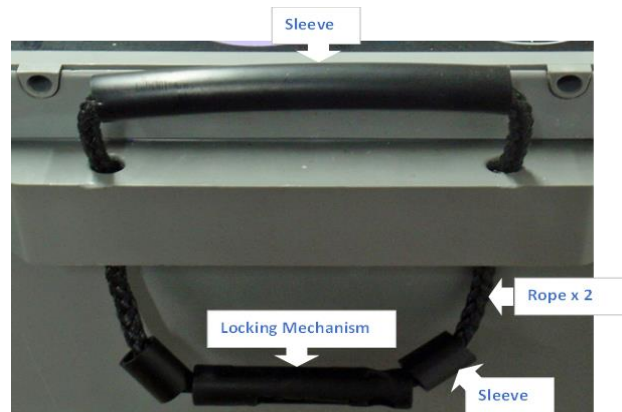


Figure 3 Handle Assembled into a Battery

2.2 Company Backgrounds

This section covers background information of the parties involved in the project to give an understanding of the use of the product in application.

2.2.1 EnerSys

EnerSys is a supplier of stored energy solutions (batteries) and covers a wide range of applications (EnerSys, 2020), including use in motive power (forklifts), mining equipment, telecom units, and security systems (EnerSys, 2019).

Figure 5 shows an image of the EnerSys SBS battery range; these are commercial batteries, with the main application being reserve power for telecoms units.



Figure 5 EnerSys SBS Battery Product Family (EnerSys 2011)

2.2.2 Customer – Daimler

Daimler, also known as Mercedes-Benz, is one of the largest automotive companies and a popular supplier of luxury cars and vans (Mercedes-Benz Group, 2022). EnerSys has supplied Daimler with NorthStar battery products since 2016 (EnerSys, 2022).

Daimler is the sole customer for the product that the handles are installed into (see Figure 4 for Daimler battery image). Therefore EnerSys must comply with Daimlers published standards related to the handle. These batteries are installed in electric Mercedes trucks.

Daimler and EnerSys have previously worked together to create the world's first Ultra High-Performance Pure Lead AGM design with a wireless battery management system. The system had a positive impact and resulted in zero battery failures in the Mercedes Actros and Actros models (see Figure 6 for an image of an Actros truck) (EnerSys, 2022).



Figure 6 Mercedes Actros Truck (sparshattgroup, 2019)

2.2.3 Supplier – Rope and Plastics

Rope and Plastics have been manufacturing handles for over 20 years for the automotive industry and have two manufacturing facilities, one in North Carolina and one in Malaysia (Rope and Plastic Group, 2022).

2.3 Project Brief

Following routine tensile testing of a rope handle performed by EnerSys France, it was found that the strength of the handles in the latest batch of samples is significantly lower than previously received batches. Generally, tensile testing of the product is performed for each batch of 20000 samples by the supplier and less frequently by EnerSys. The handle is employed in a product used solely by Mercedes/Daimler.

Due to supply chain issues, EnerSys will need to use handles with a new rope (see Figure 3 for an image of rope) for the foreseeable future (the supplier will not be able to obtain the original rope; see section 10.2). Sourcing out a new supplier or changing to the old rope is not possible in the short term and will cause delays in production/cause orders not to be fulfilled, which heavily impacts company profits as the handles are used on a popular product. This information was discovered following a meeting with the supplier to discuss the possible root causes (this can be found in section 10.0).

This engineering project aims to determine the best short-term and long-term actions to take regarding a supply chain and performance issue.

It has been tasked upon the EnerSys Newport Design team to assess whether the new batch of handles meets the required/relevant standards that Daimler and the European Union have set out, as well as EnerSys's own standard of achieving a factor of safety of 3 (the design authority set this standard across all products after an accident occurred with a product in application). It must also be determined through testing whether the handles from the latest batch can be used in production under a concession/deviation request whilst also working towards a long-term solution to the initial issue. The risk factor involved with allowing a concession for this batch of samples is determined by defining where the baseline strength of the currently supplied handles lies.

It was found that the testing methods used by EnerSys France and the supplier were not aligned with each other and gave significantly different results. It is essential to establish whether either party's testing accurately represents the application of the handle in question and to align the test methods of all parties by either producing a new test method or using the correct method of the two parties.

2.4 Project Aim

To maintain supplying battery handles that comply with Daimler's specifications with a sufficient and consistent safety factor/quality until a long-term solution is implemented.

2.5 Project Objectives

- Determine whether or not the latest batch of handles complies with the minimum required specification set out by the customer (Daimler) and the EN standards. This will involve the alignment of test methods between all parties, using hand calculations to determine the current safety factor and performing a rudimentary test to verify that the hand calculations are correct. Testing will involve a static load test/tensile test to the EN and Daimler standards and include capability data and comparison of results between batches and supplier/partner plant results.
- Inspect and compare the new handles to the previous batch to help determine the root cause of the decrease in tensile strength. Performing research into the handles' moulding process and the assembly's design will also help determine the root cause of the decrease in strength.
- Determine whether the handles are acceptable for use under a concession and develop a short-term suitable quality control procedure to ensure the handles consistently meet the required specifications.
- Produce a forward plan for a long-term solution (new supplier/design change/use of old rope if possible).
- Provide recommendations to the supplier regarding how to move forward.
- Eliminate all risks of handles not meeting the relevant specifications and keep production going without any significant delays.
- Perform a parts production approval process on the new batch of samples after any changes are made, which involves performing all relevant testing and inspections to compare with historical data to ensure that the samples are back in line with or improve upon what was historically used.
- Understand how to stop a supply issue such as this from reoccurring.

2.6 Product Application

This section gives some oversight into the application of the product the handles are used on to emphasise the importance of this product.

The batteries produced for Daimler that employs the handle shown in Figures 3 & 4 are used to power the auxiliaries in Daimler electric trucks.

For most electric vehicles, low-voltage lead-acid batteries (also known as auxiliary batteries) are a vital component of the multi-battery system present in the vehicle. In combination with the high-voltage battery system, low-voltage electric vehicle batteries ensure the vehicle can function and provide power for critical safety features (batteryinnovation, 2022).

Auxiliary batteries play a crucial function for hybrid and electric vehicles, and lead-acid batteries offer several key strengths in this application compared to other technologies.

The 12V auxiliary lead-acid battery provides backup power for safety-relevant features such as power steering and brake boosting. However, they are also essential for secondary features such as radio and sound systems (batteryinnovation, 2021).

In the event of the failure of the main battery, the auxiliary lead-acid battery takes over. It powers the vehicle's safety features to enable the car to safely pull over (batteryinnovation, 2021).

As a technology, lead acid batteries are safe and reliable, and safety is vital in motor vehicle applications (batteryinnovation, 2021).

2.6 Product Application

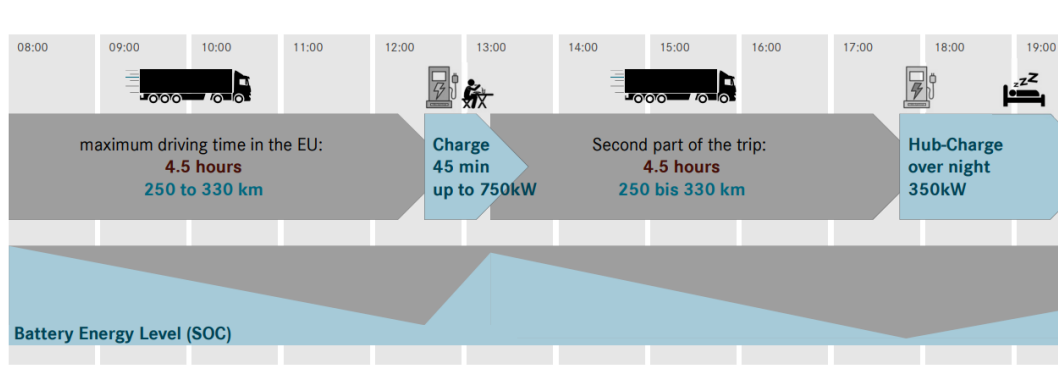


Figure 7 Typical Battery Energy for Daimler Trucks (Mercedes-Benz Group, 2021)

Figure 7 shows the typical time an electric truck will run before needing to charge. During the charge time, the EnerSys battery becomes functional and powers the auxiliaries of the truck.

The handle assessed in this project is used in all Daimler truck batteries; therefore, they must meet Daimler and EnerSys' set standards, as failure in the application can cause the 69KG battery to fall and either hurt a person or damage the internals of an electric truck.

3.0 Project Plan



Project Plan Summary

Status Colour Legend

Not Started	In Progress	Complete
ON	ON	ON

Task	Status	Anticipated Start Date	Anticipated End Date
1 - Comparison of Testing Methods and Production of New Testing Method	Complete	04/09/2022	11/09/2022
2 - Performing all relevant testing and hand calculations/stress calculations	Complete	04/09/2022	11/09/2022
3 - Production of a visual aid document detailing visual Quality Requirements for 100% checking of samples if deviation request is accepted (was developed and updated throughout the project)	Complete	04/09/2022	01/10/2022
4 - Produce a Testing Report compiling and comparing all testing data from all parties and detailing new findings from testing results obtained at EnerSys Newport	Complete	04/09/2022	11/09/2022
5 - Meeting with all involved EnerSys employees to discuss testing results and short-term plan (i.e. whether acceptance of a deviation request is feasible based on testing results)	Complete	11/09/2022	11/09/2022
6 - Determine the Root Cause of the loss of strength	Complete	12/09/2023	19/09/2022
7 - Produce a forward plan and assign responsibilities to all parties involved based on data gathered from previous tasks	Complete	22/09/2022	26/09/2022
8 - Establish Screening Method for EnerSys Arras	Complete	03/10/2022	07/10/2022
8 - Determine screening costs and discuss compensation from the supplier for samples not meeting EnerSys requirements.	Complete	15/10/2022	26/10/2022
9 - Allocate screening responsibilities to the supplier whilst agreeing with requirements.	Complete	26/10/2022	26/10/2022
10 – Discuss the production of handles with alternative suppliers.	Complete	04/11/2022	18/11/2022
11 - Completion of Verification of New rope from alternative suppliers to be used by Rope and Plastics (2 suppliers from China failed, and one supplier from Germany shows promising results)	Completed – Due to issues, the supplier has stopped pursuing this venture.	04/11/2022	25/11/2022
12 - Discuss which design supplied by LER (new supplier) to prototype	Complete	02/12/2022	02/12/2022
13 - Update specifications and drawings so Accuma (new supplier) can start processing the request to produce these handles	Completed	02/12/2022	16/12/2022
14 - Test Prototype of New Design from LER (one sample only has been received)	Completed	15/12/2022	15/01/2023
15 - Test prototype design from Accuma (awaiting new handle design)	Not Received		
16 - Perform a PPAP approval on new rope samples supplied by Rope&Plastics (awaiting a new handle design)	Not Received	10/01/2023	24/01/2023

Based on the parts production approval report, additional tasks may need to be completed

Table 1 Project Plan

3.0 Project Plan

Table 1 consists of the general plan for this project.

Tasks 1-13 were completed without issues and within the expected end dates.

The current supplier tried to outsource and assess multiple ropes similar to the originally supplied rope. Unfortunately, none of the alternatives was acceptable, and as of January 2023, the project was put on hold for higher priority projects that affected both EnerSys Newport and EnerSys France plants.

Task 14 was completed by Awais Ahmed in April of 2023, which is much later than anticipated due to project priorities.

Task 15 has not progressed as the alternative supplier Accuma as of May 2023 has yet to provide an alternative handle design.

As of May 2023, the current supplier has found two alternative rope suppliers that have passed preliminary testing and will be sent to EnerSys Newport to assess.

3.1 Team Structure

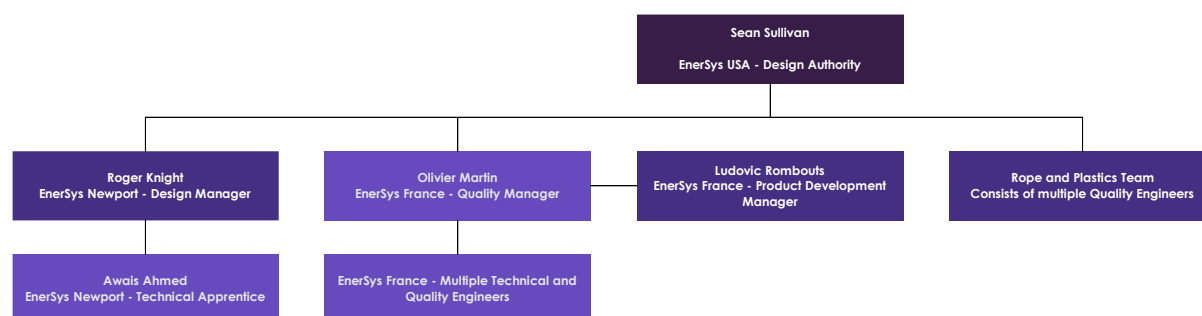


Figure 8 Team Structure Diagram

3.2 Work Completed by Each Party

Awais Ahmed	Sections 1-4.3 Sections 4.5-5.4 Sections 10.0 & 14.0 Sections 20.0-29.0
Awais Ahmed Roger Knight	Section 4.4 Section 6.0 Section 8.0 & 9.0 -The test method was developed by Roger Knight. Testing was performed by Awais Ahmed and Roger Knight. Analysis was performed by Awais Ahmed. Section 11.0, 12.0 & 13.0 Measurements and calculations were performed by Awais Ahmed and Roger Knight, analysis was performed by Awais Ahmed. Sections 15.0 & 16.0
Awais Ahmed EnerSys France Team	Sections 17.0, 18.0 & 19.0 results were obtained from the EnerSys France team and analysed by Awais Ahmed.
EnerSys France Team	Section 5.1.1
EnerSys France Team Rope and Plastics Team Awais Ahmed	Section 7.0 - Results are obtained from testing performed by the EnerSys France Team and Rope and Plastics Team. Analysis was performed by Awais Ahmed.

4.0 Methodology – Testing Method and Standards

4.1 Test Method Background Information - Relevant Standards

Before assessing the test results from Rope and Plastics (supplier) and EnerSys France, it is vital to establish the base requirements for the handle assembly stated on the relevant standards.

Background research was performed before the analysis of the handles to ensure that the correct testing standards were followed.

The EN 50342-2 specification covers the properties of battery housings and handles. This European Standard applies to polypropylene multicell battery housings for lead-acid batteries that are used as energy storage devices and details the relative testing requirements (EuropeanStandards, 2010).

There is also an internal Daimler specification that EnerSys must comply with for all handles used in Daimler products. This specification is similar to EN 50342-2 and refers to it throughout (Daimler, 2020).

Two relevant testing methods and requirements relating to the handle will be adhered to -
The continuous load test and sudden loading test.

This section will discuss each test's requirements and show force calculations detailing the loading at each section of the handle. This information helps develop a proper testing procedure with the correct requirements.

4.2 Continuous Load Testing

The Daimler specification in Figure 9 refers to the EN 50342-5 specification for how the continuous load test should be performed.

3.5.8	Handle strength test (NAGM-3514)
3.5.8.1	Strength of the handles tested with continuous load (NAGM-3515)
NAGM-3516	This test must be performed according to EN 50342-5 Chapter 4.4.4
NAGM-3518	The test is performed at, -30 °C, 23 °C and +50 °C, in each case with $\pm 2^\circ\text{C}$ tolerance.
NAGM-3519	The battery or lid with handle shall be fixed to the pulling device in a manner allowing one handle to be pulled up vertically. The handle is hooked into the holding plate and is connected to the pulling device. Then the handle is pulled with a speed of 50mm/min until the re-quested force has been reached. Batteries with handles fixated at the lid have to be fixed in a manner, that the welding joint between box and lid is extremely used with pulling force.
NAGM-3520	A tensile pull device with a width of 70 mm must be used.
NAGM-3521	Acceptance criteria: Three-times of the battery weight to a max. force of 800 N. Deformations of the handles are acceptable.
NAGM-3522	The test shall continue until the breaking point of handles. These breaking points shall be documented.

Figure 9 Daimler Specification for Handle Strength Test (Daimler, 2020).

EN 50342-5 states the following (see Figure 10):

4.4.4 Strength of the handles tested with continuous load

The purpose of this test is to prove the strength of the handles and their fixations to the battery for manual handling. If handles are fixed at the lid the welding of lid and box is tested additionally. The test is performed with a battery housing (box and lid welded) or fixed lid only.

The handles including their fixations to the battery should withstand to the forces that normally occur when a person transports or handles the battery. By handling the batteries with handling-apparatus and/or robots the below mentioned load limits may not be exceeded.

- **Apparatus:**
 - Climate chamber with sufficient power.
 - Pulling device (tensile test apparatus) with sufficient force.
 - Holding plate of 70 mm width.
- **Execution:**

The test is performed at, -30 °C, 23 °C and +50 °C, in each case $\pm 2^\circ\text{C}$.

The battery or lid with handle shall be fixed to the pulling device in a manner allowing one handle to be pulled up vertically. The handle is hooked into the holding plate and is connected to the pulling device. Then the handle is pulled with a speed of 50mm/min until to the re-quested force has been reached.

Batteries with handles fixated at the lid have to be fixed in a manner, that the welding joint between box and lid is extremely used with pulling force.
- **Requirement:**

Three-times of the battery weight to a max. force of 800 N.

Deformations of the handles are acceptable.

Figure 10 EN 50342-5 Specification for Continuous Load Test (EuropeanStandards, 2010)

For the assessment of the handles during this project, the testing will be performed at room temperature to ensure the relevant standards are met. Then EnerSys France will perform the follow-up testing at -30&50°C once a baseline has been established and the relevant quality control procedures have been implemented (refer to section 19.0 for the result statement).

4.3 Force Calculations for minimum acceptable requirement - Continuous Load test

Based on the information laid out in the Daimler specification and EN 50342-5, the minimum acceptable requirement for handle strength during continuous loading testing is 800N as the mass of one battery in this case is 69KG which equates to 676.6N and three times this weight is greater than 800N (EuropeanStandards, 2010) (Daimler, 2020).

Strength of Handles with Continuous Load

Daimler Test Paragraph 3.5.8.1 (Daimler no.A9640010399) (Daimler, 2020).

“Refer also to specification EN50342-5

To be tested at -30°C, +23°C and +50°C

Requirement: One Handle to withstand 3 times the weight of the battery to a maximum force of 800N.” (EuropeanStandards, 2010)

Deformation of the Handle is permitted.

Battery mass = 69KG

Battery mass X 3 = 207KG

Convert to Newtons x 9.806 = 2029.8N

The max force on the specification is stated as 800N; therefore, this is used as the minimum requirement.

Figure 11 shows the forces acting in each direction of the handle assembly.

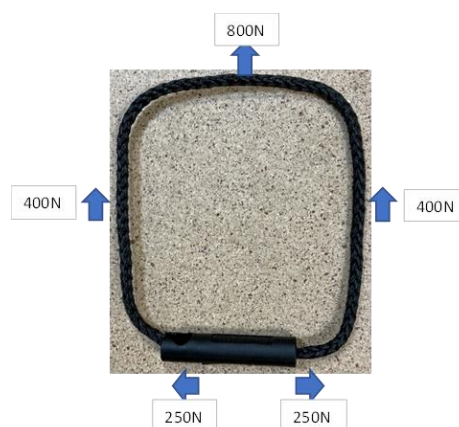


Figure 11 Force Calculations for Continuous Load Test based on minimum requirement

Note: Load applied to locking mechanism (horizontal vector force) was derived by testing (see section 4.4). Divide vertical load by 1.6 (400N /1.6 = 250N or 25.5Kg)

4.4 Derivation of horizontal load shown in Section 4.3

30 Samples were tested at EnerSys Newport using the setup shown in Figure 12 to derive a ratio to calculate the horizontal load applied to the handle assembly's locking mechanism.

The setup in Figure 12 aims to replicate how the handle assembly performs when installed in a battery. A digital force gauge was used to display the load in the horizontal direction for a given vertical load allowing a ratio to be calculated.

A machine speed of 50mm/min was used to replicate a battery being lifted slowly by a hand.

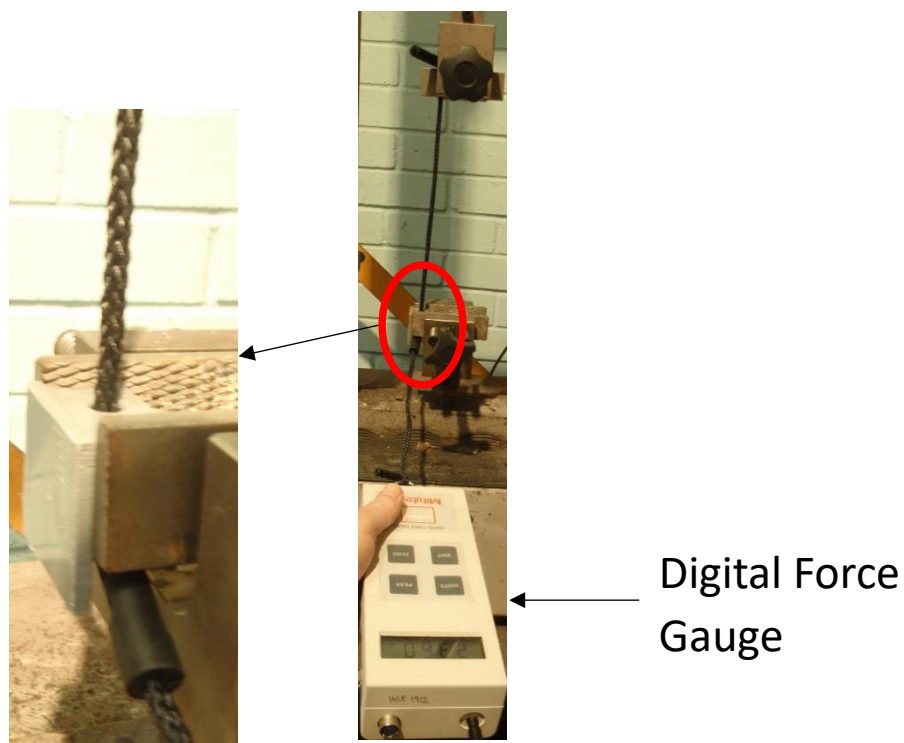


Figure 12 Test Set-up for verifying calculated Horizontal Load

4.4.1 Test Results Summary

The average result across 30 samples was 250N (refer to Appendix A Table 11 for raw data) when a 400N load was applied vertically. This results in a ratio of 1.6 between the vertical 400N load and the horizontal 250N load. This result is then compared with hand calculations using trigonometry (refer to Figure 14).

4.5 Derivation of Horizontal Load – Trigonometry method

Initially, the rope was measured horizontally and vertically using a vernier calliper after installation into a battery. The formula “Tan(theta) = Opposite/Adjacent” (Weisstein, 2001) was rearranged to calculate the angle between the vectors (refer to Figure 13).

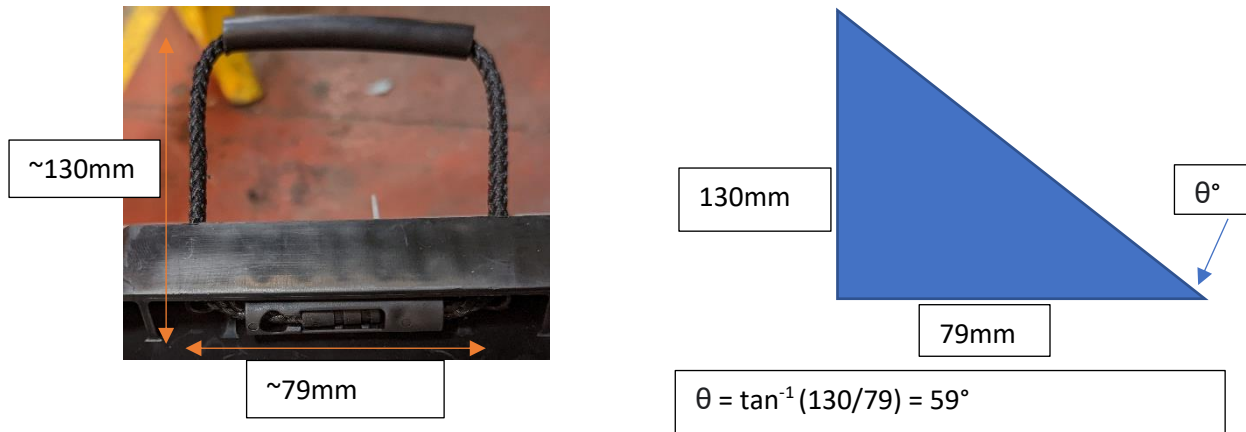


Figure 13 Rope dimensions in horizontal and vertical direction and resultant angle calculation

Trigonometry was used to perform hand calculations to compare with the physical experiment results from section 4.4. The formula “Tan(theta) = Opposite/Adjacent” (Weisstein, 2001) was rearranged to calculate the horizontal load at the locking mechanism of the handle (refer to Figure 14).

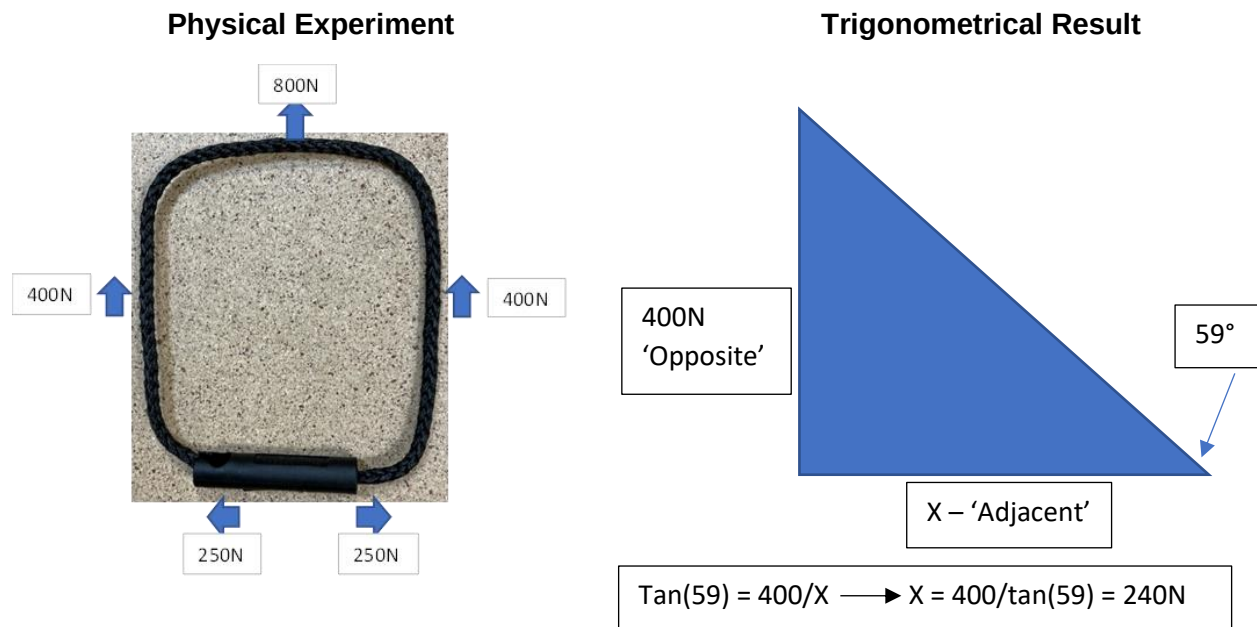


Figure 14 Comparison of Physical Testing Results and Hand Calculations

The difference between the trigonometrical method and the physical experiment is less than 4% giving confidence in the calculated ratio.

4.5.1 Difference in Results

The slight difference in results between the physical experiment and hand calculations can be accounted for by factors trigonometry does not consider, such as:

Friction creates additional resistance that affects the tension in the rope. The trigonometrical calculation used in Figure 14 assumes that the rope is passing through a frictionless surface, giving a lower tension force in the rope than what would be seen in reality (Harvard University, 2015).

Trigonometry assumes that the rope is inextensible, whereas most ropes will have some degree of elasticity in reality. As a rope is placed under tension, it will stretch slightly, which can affect the tension in the rope as tension is similar to elastic potential energy (Energy Education, 2018).

Trigonometry assumes that the load on the rope is static, meaning that it is not moving or changing ([1]TWI, 2022). In reality, loads on a rope can be dynamic, with sudden changes in direction (suddenly swinging from one end) that create additional stresses on the rope ([2]TWI, 2022).

Trigonometry does not consider the effects of temperature or other environmental factors that can affect the tension in a rope. These factors can cause the tension in a rope to vary over time and may need to be considered in certain situations, such as when a battery is used in a very hot country. This heat can reduce the rope's strength (Marlow Ropes, 2016).

An error could be induced due to how the angle was derived. A vernier calliper was used to measure the length of the rope at the horizontal and vertical sections. The measurement was an estimate as it is difficult to measure these sections when installed into a battery accurately.

4.6 Sudden Loading Test Method

The second test requirement in the relevant standards is related to a sudden loading test where a battery is left to swing freely from a surface whilst being held up by a single handle. Figure 15 shows the Daimler specification information.

3.5.8.2	Strength of the handles tested with sudden load (NAGM-3523)
NAGM-3524	This test must be performed according to EN 50342-5 Chapter 4.4.5
NAGM-3525	This test should be carried out using 3 batteries of the same type that have been stored at -30 °C, 23 °C and 60 °C for a minimum of 12 h. The test must be done immediately after the battery is taken out of the storage room.
NAGM-3526	Acceptance criteria: The handles of the battery must withstand the test without damage or rupture.
NAGM-3527	<i>The personnel running this test must be equipped with sufficient personal security equipment to be prepared if the handle breaks and the battery falls to ground.</i>

Figure 15 Daimler Specification Sudden Load Test (Daimler, 2020)

The referenced EN 50342-5 Chapter 4.4.5 from the Daimler specification is shown in Figure 16.

4.4.5 Strength of the handles tested with sudden load

The purpose of this test is to establish what happens if one handle of a battery is suddenly subjected to the total weight of the battery plus the momentum resulting from the battery falling a set defined distance. This happens if the battery is pulled out of a storage rack. The battery is placed on a mobile table. The battery is attached with a steel wire rope and a slit steel tube or adequate support (length 70 mm, diameter depending of the thickness of the handles, at least some space between 1 mm - 2 mm more than diameter). The mobile table is moved suddenly until the battery drops. Instead of a mobile table also a crane can be used to pull the battery

This test should be carried out using 5 batteries of the same type that have been stored at -30 °C, 23 °C and 60 °C for a minimum of 12 h. The test must be done immediately after the battery is taken out of the storage room.

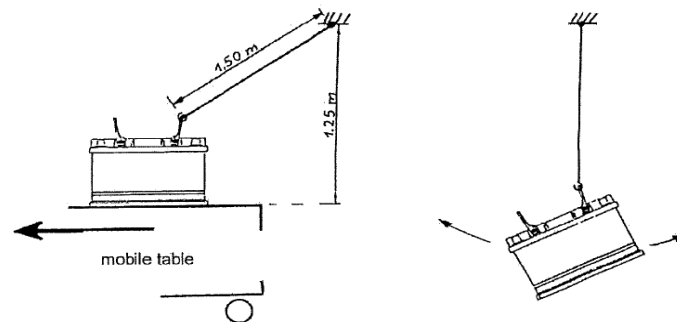


Figure 2 – Sudden load test

- **Requirement:** The handles of the battery must withstand the test without damage or rupture.
The personnel running this test must be equipped with sufficient personal security equipment to be prepared if the handle breaks and the battery falls to ground.

Figure 16 EN 50342-5 Specification Sudden Load Test (EuropeanStandards, 2010)

As stated in section 4.2, testing at the maximum and minimum temperatures will be performed at EnerSys France. The tests will be performed directly in line with the Daimler and EN specifications. The test methods currently used ensure that the samples meet EnerSys's factor of safety of 3, which ensures that the samples are guaranteed to meet the requirements stated in Figure 16.

4.7 Force Calculations for minimum acceptable requirement - Sudden loading test

Strength of Handles with Sudden Load

Daimler Test Paragraph 3.5.8.2 (Daimler no.A9640010399) (Daimler, 2020)

“Refer also to specification EN50342-5

To be tested at -30°C, +23°C and +50°C

Requirement: Sudden load applied to one handle.

No damage or rupture permitted.” (EuropeanStandards, 2010)

Battery mass = 69KG

Convert to Newtons $\times 9.806 = 676.6\text{N}$

Figure 17 shows the forces acting in each direction of the handle assembly.



Figure 17 Force Calculations for Sudden Load Test

Note: The load applied to the locking mechanism (horizontal vector force) was derived by testing. Divide vertical load by 1.6 ($338.5\text{N} / 1.6 = 211.5\text{N}$ or 21.6Kg). The calculation does not consider dynamic loading from sudden weight application. Therefore as this is a sudden application of load, it must be considered that the strain will be doubled, so a safety factor of two must be considered (refer to section 4.7.1 for additional information) ([1]Lake, n.d.).

4.7.1 Reasoning why stress is doubled during sudden application of load

This section considers a bar subjected to a sudden load; it will be the same case for a battery.

“P = Load applied suddenly

A = Cross-sectional area of the bar

l = Length of the bar

E = Modulus of elasticity of the material

δ = Deformation of the bar

σ = Stress induced by the application of the sudden load”

The load (P) will be consistent throughout the deformation of a bar since it is applied suddenly (aligarh muslim university, 2021).

Therefore, “Work done = Force × Distance = Load × Deformation = P × δl” (aligarh muslim university, 2021).

Energy Stored is defined by the formula below

$$“ U = \frac{\sigma^2}{2E} \times Al ” \quad (\text{aligarh muslim university, 2021})$$

The stored strain energy will be equal to the work done which gives the resulting formula below (aligarh muslim university, 2021).

$$“ \frac{\sigma^2}{2E} \times Al = P \times \delta l = P \times \frac{\sigma}{E} l ”$$

or

$$\sigma = 2 \times P/A “ (\text{aligarh muslim university, 2021})$$

The formula above means that the resulting stress from a sudden application of loading will give twice the induced stress that is seen during a gradual application of loading (aligarh muslim university, 2021).

4.7.2 Reason for testing at different temperatures

The reason for the temperatures that the handle has to be tested to is due to the battery specification, as the battery itself must perform as expected within this temperature range. If the battery must perform as expected at these temperatures, the same is expected of any additional parts. EnerSys batteries are used worldwide in countries such as Canada (daily average can be as low as -15°C (Weather & Climate, 2019), where the temperature is really low and places such as Qatar, where temperatures can reach a maximum of 50°C (climatestotravel, 2022).

The higher the temperature, the more current a lead acid battery will accept; this will reduce the life of the battery due to grid corrosion. For every 10°C increase, the current is doubled, which results in halving the battery life (blueboxbatteries, 2015).

Low temperatures result in reaction rates within the battery slowing down, which means that more energy will be required for reactions. This results in a lower charge capacity and the battery ultimately underperforming (McDonagh, 2021).

4.8 EnerSys Testing Requirement

Based on the requirement set out by the Design Authority in EnerSys, the results of the loading tests must meet a factor of safety of 3 as a minimum for the continuous loading test. Only the requirements laid out in the relevant specifications for the continuous loading test were considered to meet this requirement, as this test had the highest loading requirements.

Below is the minimum acceptable loading that the handle must comply with to meet a factor of safety of 3.

Requirement: One Handle to withstand 3 times the weight of the battery

Battery mass = 69.0Kg

Battery mass X 3 = 207.0Kg

Convert to Newtons x 9.806 = 2029.8N



Figure 18 Force Calculations for Continuous Load Test Following EnerSys' requirement

Note: Load applied to locking mechanism (horizontal vector force) was derived by testing.

Divide vertical load by 1.6 ($1005\text{N} / 1.6 = 628\text{N}$ or 64Kg)

Safety factor of 3 at Locking Mechanism = 634N

Safety factor of 3 at Rope at Vertical Section = 1015N

The results from the calculations shown in Figure 18 show the minimum acceptable standard set out by EnerSys for the load at each point of the handle.

4.9 Current EnerSys Standard

Currently, the samples are tested to the loading values below, as stated on EnerSys design drawings related to the handle.

The locking mechanism strength minimum value is set at 800N (calculated minimum to comply with EnerSys FOS = 634.3N).

The rope strength has a set minimum value of 1500N (calculated minimum to comply with EnerSys FOS = 1015N).

The reason for the original requirements being set so high was as follows:

The original rope handles supplied to EnerSys had results of 978-1100N for the continuous loading test at the locking mechanism; therefore, the minimum requirement was set to 800N. The rope withstood loads greater than 2000N; therefore, the minimum requirement of the rope strength was set to 1500N. Unfortunately, historical data for samples tested in the past is very small; therefore, a capability study cannot be performed accurately. This report has results for the originally supplied rope, and a capability study was performed (refer to Figure 31).

The factor of safety of 3 is from requirements the design authority set for large product types, and it is based on historical issues with handle failures from other product types during application. It was implemented to reduce the risk of failure when EnerSys products are in the customer's hands.

Ropebook (Ropebook, 2019) and physics problems (problemsphysics, 2020) were used as sources of information to help perform force calculations on the handle assembly and to also give information on the reason why the supplier test method and EnerSys France are not acceptable (see section 5.0).

4.10 Summary of this section

The baseline requirements for the tensile testing of the handles in order to meet all requirements set out by EnerSys and the customer/EN have been established.

The EnerSys requirements state that the samples must comply with a factor of safety of 3. This requirement is standardised across all EnerSys products by the design authorities due to products failing in application in the past.

5.0 Methodology - Comparison of Testing Methods between EnerSys France and Supplier

There is a difference in results between the supplier and EnerSys France. This section details each test method's weaknesses and compares the methods' results. A new testing method is proposed to ensure that the supplier and EnerSys are aligned.

5.1 Supplier Test Method

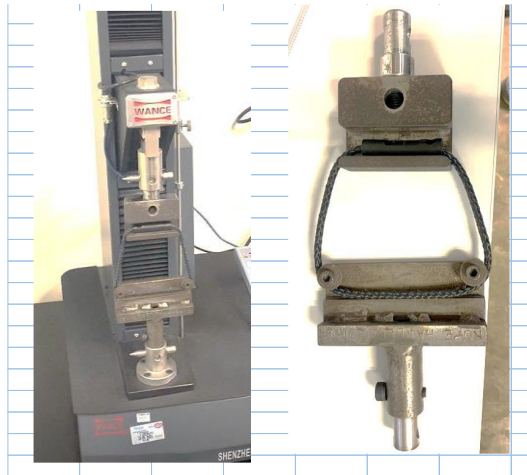
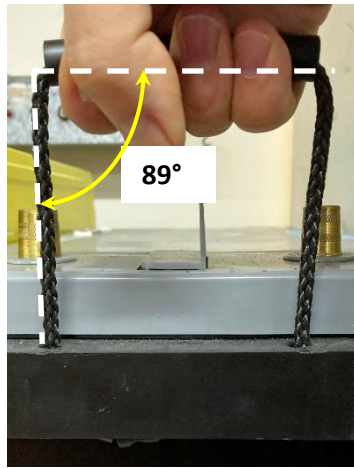


Figure 19 Supplier (Rope and Plastics) Test Set-Up for Continuous Load Test

Initially, the supplier used the test method above and obtained a minimum result of 569N for the tensile strength of the locking mechanism. This is 231N below the EnerSys requirements and is a significant decrease compared to the previously supplied handles.

5.1 Supplier Test Method

Handle installed in battery



Supplier Test Method

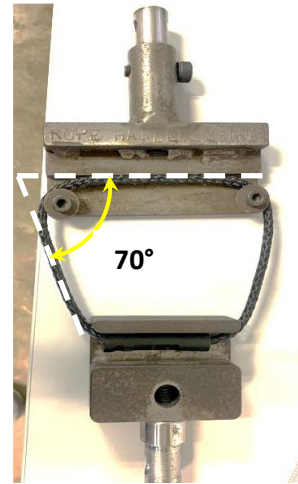


Figure 20 Comparison of Rope angle between supplier Test Set-up and battery installation

The main issue with this test method is that it needs to directly assess the strength of the locking mechanism, which is the weakest point of the part. It assesses the strength of the handle assembly, but it is not orientated similarly to when the handle is installed in a battery; this results in differing vector angles, as shown in Figure 20, which will induce a different horizontal load value on the locking mechanism. As the angle is greater at the locking mechanism, more loading will be applied horizontally, resulting in the part failing at a lower observed load. Therefore, this test method will not be used as a standard for both parties.

5.1.1 Supplier Test Method Results (5 samples) for reference

Results			
Sample #	Result (KgF)	Result (N)	Remark
1	199.76	1959.65	Rope broken from plastic handle
2	185.43	1819.07	Rope broken from plastic handle
3	191.38	1877.44	Rope broken from plastic handle
4	205.12	~~2200.45~~ 2011	Rope broken from plastic handle
5	201.50	1976.72	Rope broken from plastic handle
Average	196.64	1929.04	All samples are passed

Load Vectors by calculation based on minimum result			

Figure 21 Small Sample Size of Supplier results for the continuous load test (tested to a factor of safety of 3)

5.2 EnerSys Test Method

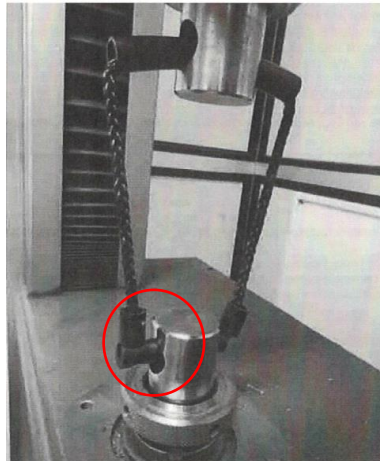


Figure 22 EnerSys France Test Set-Up

In the test set-up shown in Figure 22, the way the handle is held within the machine places additional strain through the centre point of the locking mechanism, which will cause additional stress. The stress applied to the centre of the locking mechanism will be a vertical load. The part will withstand a greater load due to a different type of deformation being exhibited to a thick point (the cavity). The locking mechanism also has not been fitted correctly; see the area circled in red in Figure 22. Therefore the strength of the locking mechanism is contingent on the correct fitting.

EnerSys France advised that they obtained a minimum result of 750N, which is almost a 200N increase to the supplier results and is still below the minimum required standard.

The forces are not acting the same as in reality; horizontal forces act on the locking mechanism, as seen from the assembly shown in Figure 23. In Figure 22, a direct vertical load will be applied to the locking mechanism, which does not reflect what occurs during the actual application of the part.

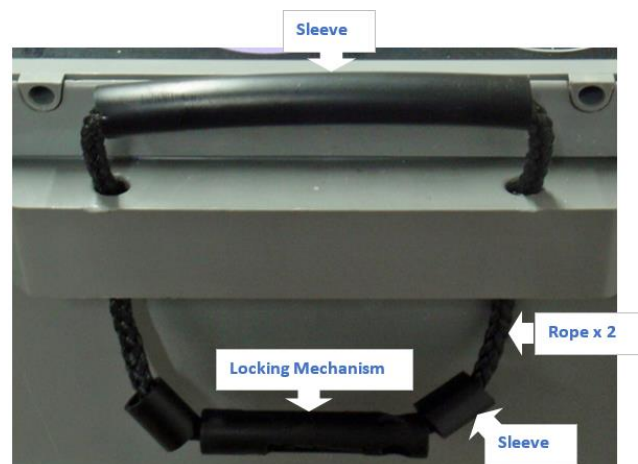


Figure 23 Handle Installed into a Daimler Battery

5.3 New Proposed Test Method by EnerSys Newport

Both test methods used by EnerSys France and Rope and Plastics (supplier) have inherent flaws; a new method is proposed to align the testing performed at each party.

The test procedure is similar to the current test methods used at EnerSys France and Rope and Plastics (supplier); however, the inherent disadvantages of each parties methods are accounted for and will not negatively impact the results.

5.4 Reasoning/benefits of Test method alignment

The testing process can be more consistent and reliable by aligning test methods with a supplier. The supplier can identify issues earlier, and the results will be trusted as a verified testing process has been used. This will ultimately lead to better quality control.

If the supplier's testing method is trusted, duplicate testing can be avoided (both supplier and customer performing the same test), reducing costs and improving efficiency. This would be in the case of general testing; whenever a product does not comply with the relevant specification, a new product is being introduced or a product supplier/design change has occurred, then both the customer and supplier will need to perform testing and agree on whether the product is fit for purpose. This is standard practice at EnerSys.

6.0 Methodology - New Proposed Test Method by EnerSys Newport

This section will detail the test procedure of the part as well as include the requirements that need to be met based on EnerSys' current standard. A deviation request will need to be made for the currently supplied handles. This test method was produced by the EnerSys Newport team with the goal of testing alignment between all involved parties. This test method was chosen as all parties can replicate it using tensile machines, and it eliminates the errors induced by currently used testing methods.

1. PURPOSE.

- 1.1. To ensure Rope Handle will withstand specified load requirements.

2. EQUIPMENT

- 2.1 Digital Force Machine with the capability of measuring between 0 and 5000N

3. TEST SAMPLE.

- 3.1. Use Rope Handle samples manufactured to drawing HAN0029.
- 3.2. Refer to tables 2-3 for method to prepare samples.

4. PROCEDURES.

- 4.1. Health and Safety Note:
 - 4.1.1. Care should be taken when applying the test load to the Rope Handle. Ensure the Rope is securely clamped before application of load.
- 4.2. Conduct testing at a temperature of $25^{\circ}\text{C} \pm 3^{\circ}\text{C}$
 - 4.2.1. Rope Test - refer to Table 2.
 - 4.2.2. Locking Mechanism Test - refer to Table 3.

5. FREQUENCY OF TESTING

- 5.1. Supplier shall repeat both tests defined in Tables 2 and 3, 5 times per day, or 5 times per batch should the production run not last a full day (all test samples are to be discarded).

6. TEST REQUIREMENT.

- 6.1. Rope Strength Test
 - 6.1.1. The Rope must withstand a minimum load of 1500N without any fractures of the Rope Strands.
- 6.2. Locking Mechanism Test
 - 6.2.1. The Locking Mechanism must withstand a minimum load of 800N over 5 cycles without any damage / displacement of the joint or fractures of the Rope Stands.

6.0 Methodology - New Proposed Test Method by EnerSys Newport

Rope Strength Test - Test Procedure

	Photographs of Procedure	
1		Select a Rope Sample as shown.
2	  	Place the sample into a Tensile Testing Machine as shown. Position the End Mouldings as shown above and below the clamping jaws to avoid slippage during application of Tensile load. Subject the sample to a Load of 1500N using a rate of 50mm per minute. Ensure the rope is not clamped onto, as this will affect the results.
3	The Load test is to be repeated 5 times (each test with new Handle samples).	
4	Results are to be recorded on an appropriate Record Sheet and retained with batch information for future reference.	
5	The Rope Handles that are subjected to this test are to be scrapped.	

Table 2 Rope Strength Test Procedure

6.0 Methodology - New Proposed Test Method by EnerSys Newport

Locking Mechanism Test - Test Procedure

	Photographs of Procedure	
1		Select 2 Rope Handles and tie 2 knots in the highlighted positions, 1 to 2 inches from each end moulding as shown.
2		Join both Handle samples at Locking mechanism.
3	 Cyclic Load Test Number of Cycles = 5 Load Rate = 50mm per minute Loads = 0N to 800N	Place the Sample into a Tensile Testing Machine as shown. Position the 2 knots above and below the clamping jaws to avoid slippage during application of Tensile load. Subject the sample to the cyclic load test shown.
4	The Cyclic test is to be repeated 5 times(each test with new Handle samples).	
5	Results are to be recorded on an appropriate Record Sheet and retained with batch information for future reference.	
6	The Rope Handles that are subjected to this test are to be scrapped.	

Table 3 Locking Mechanism Test / Continuous Load Test Procedure

7.0 Results and Analysis after test method alignment

7.1 Supplier Test Results – For Reference

After establishing a universal test method, results can be obtained, compared and discussed.

Figure 24 shows some examples of failure modes the supplier has taken images of (load results were obtained and compared in section 7.2).

It is noted that all sample failures occurred at the locking mechanism.



Figure 24 Images Supplier took of failure modes of samples that have undergone the locking mechanism test

The numbers in Figure 24 refer to sample numbers and are there for reference.

7.2 Comparison of EnerSys and Supplier results post-test method alignment

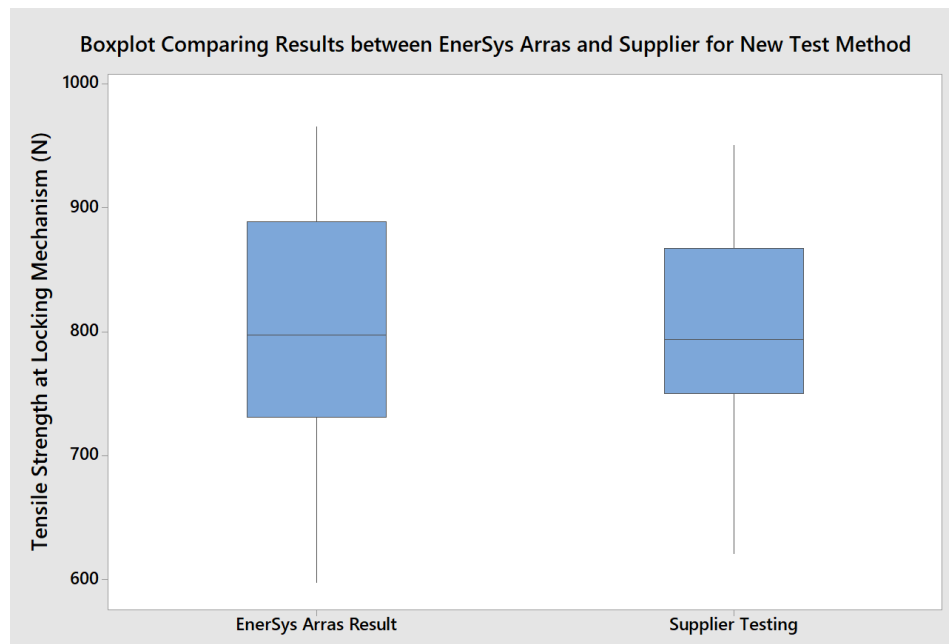


Figure 25 Boxplot comparing results between EnerSys France and Supplier for new Locking Mechanism Strength Test

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
New Handle Strength	30	798.7	97.7	18
C4	30	793.3	86.9	16

Estimation for Difference

Difference	95% CI for Difference
5.4	(-42.4, 53.2)

Test

Null hypothesis	$H_0: \mu_1 - \mu_2 = 0$		
Alternative hypothesis	$H_1: \mu_1 - \mu_2 \neq 0$		
T-Value	DF	P-Value	
0.23	57	0.821	

A low T-value and high P-value (greater than 0.05) indicate that the mean and standard deviation for the two data sets are similar, and there is no significant difference between them (Hayes, 2022; Minitab, 2015).

Figure 26 Statistical Analysis of Difference in Results between EnerSys France and Supplier

The difference in results between EnerSys and the supplier can be attributed to the large variation in sample quality seen in section 7.3 of this report. These results indicate no significant difference between the results observed for EnerSys France and Rope and Plastics; therefore, the test methods are consistent and aligned.

See Appendix A, Figure 72 for EnerSys France/Arras raw data and Table 9 for supplier raw data.

7.3 Distribution of EnerSys Results - Results comparison with previous batch

7.3.1 Currently Supplied Handles

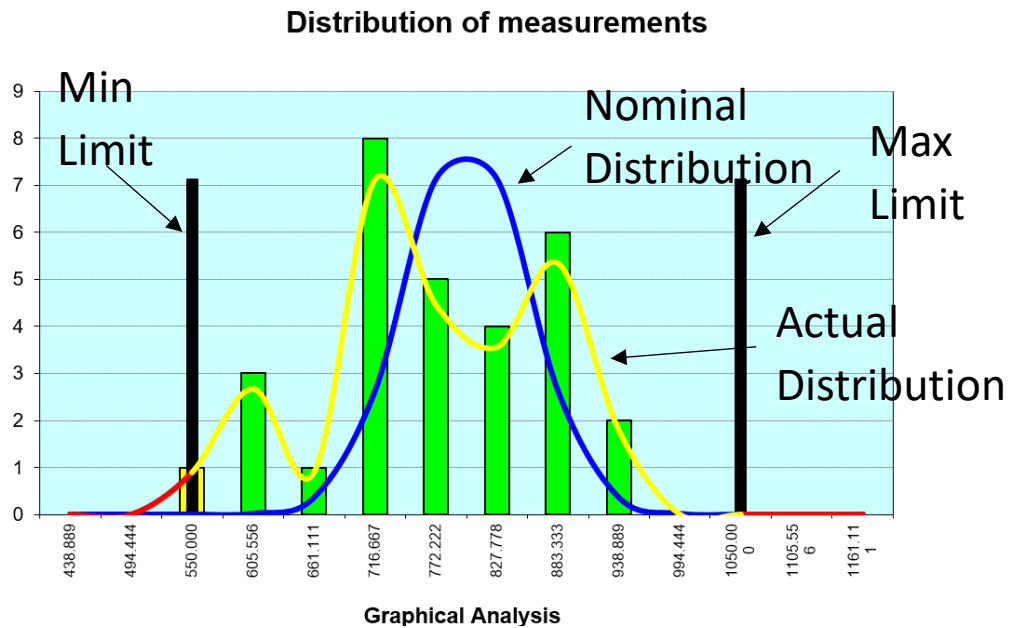


Figure 27 Locking Mechanism Test - Distribution of Results for New Rope

7.3.2 Previously Supplied Handles

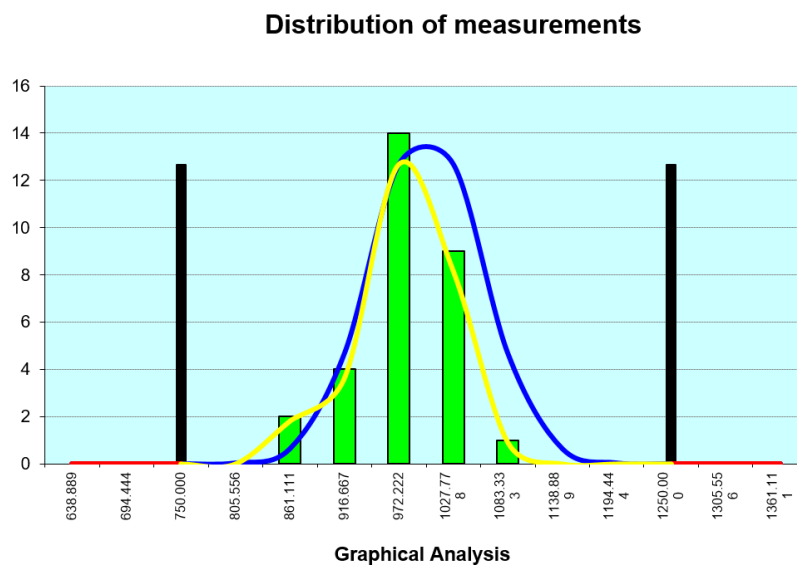


Figure 28 Locking Mechanism Test - Distribution of Results for Old Rope

The graphical data in Figures 27 & 28 shows a significant difference in strength between the currently supplied and previously supplied handles. However, another point of interest is the distribution of data. The previously supplied handles (figure 28) give a normal distribution, whereas the currently supplied handles (figure 27) give a non-normal distribution which indicates variation in the quality of the samples due to the manufacturing process.

See Appendix A Figure 72 for raw data.

7.4 EnerSys Results - Results comparison with previous batch

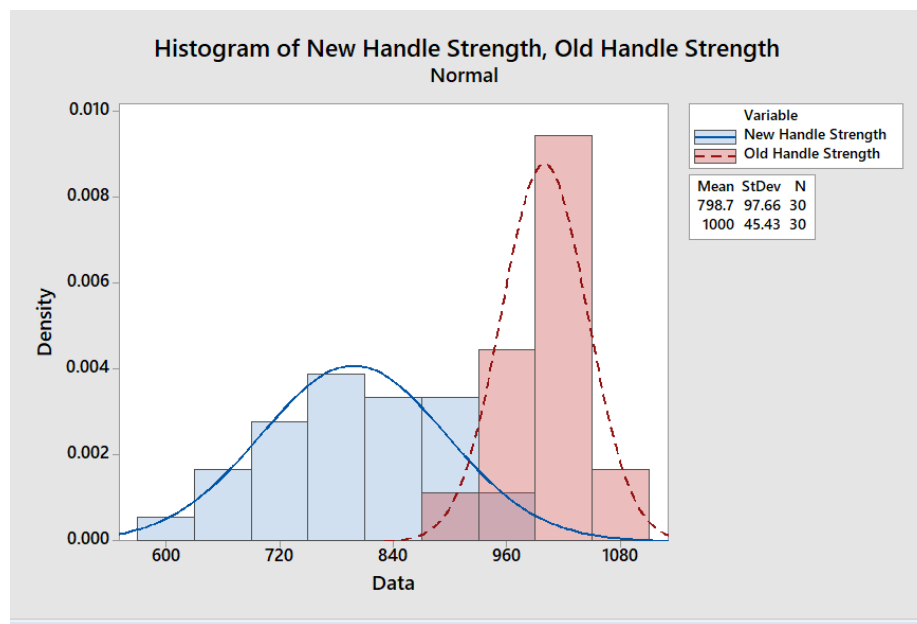


Figure 29 Histogram - Comparison of Results between New Rope and Old Rope for Locking Mechanism Strength Test

Based on Figure 29, it can be seen that there is a significant decrease in the strength of the new handle (currently supplied handle). The first course of action is to determine whether they are still fit for purpose and whether a concession by the design authority will be allowed. A more in-depth analysis of results is shown further in this section, comparing the Cpk and Ppk values between the results of 30 samples of the currently supplied and previously supplied handles.

See Appendix A Figure 72 for raw data.

7.4 EnerSys Results - Results comparison with previous batch

The chosen lower limit for the capability studies with this report is based on the minimum obtained value from testing the locking mechanism (at EnerSys France) for the currently supplied handles. The Design Manager at EnerSys Newport suggested that this value (600N) will be used as a baseline for a deviation request. The upper limit chosen (1500N) is an arbitrary number; the purpose of this value is to assess the process's capability. In reality, there will only be a minimum specified value to be met for testing requirements; however, an upper limit, in this case, needs to be inputted to calculate the Cpk and Ppk values.

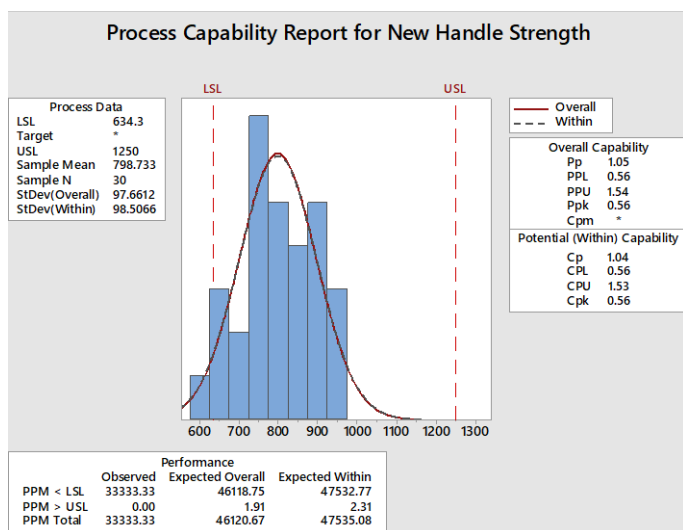


Figure 30 Capability Study of Locking Mechanism Test Results for the currently supplied handle

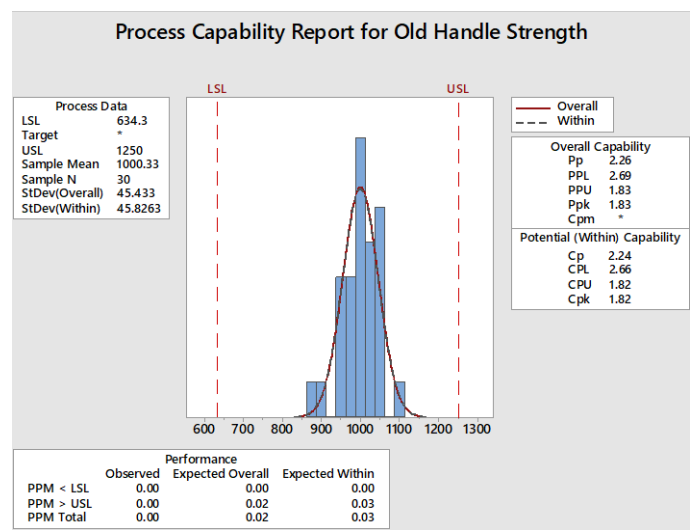


Figure 31 Capability Study of Locking Mechanism Test Results for the previously supplied handles

Results shown in Figure 30 indicate that the manufacturing process is 'not capable' for the currently supplied handles, and the variation is much larger than is considered acceptable. The previously supplied rope (Figure 31) manufacturing process is much more capable with less variation and is within specification.

Cpk is used to assess the performance of a process if there are short-term sources of variation, also referred to as machine variation (Hachmöller, 2022).

Ppk considers the long-term variation, such as temperature and supplier changes, and indicates what performance can be expected from the process overall (Hachmöller, 2022).

A Cpk value of less than 1.33 is not considered capable, and a Cpk above 1.33 is considered capable (Minitab, 2017).

See Appendix A Figure 72 for raw data.

8.0 Methodology - EnerSys Newport Testing (Factor of safety of 3 physical test)

8.1 Test Method

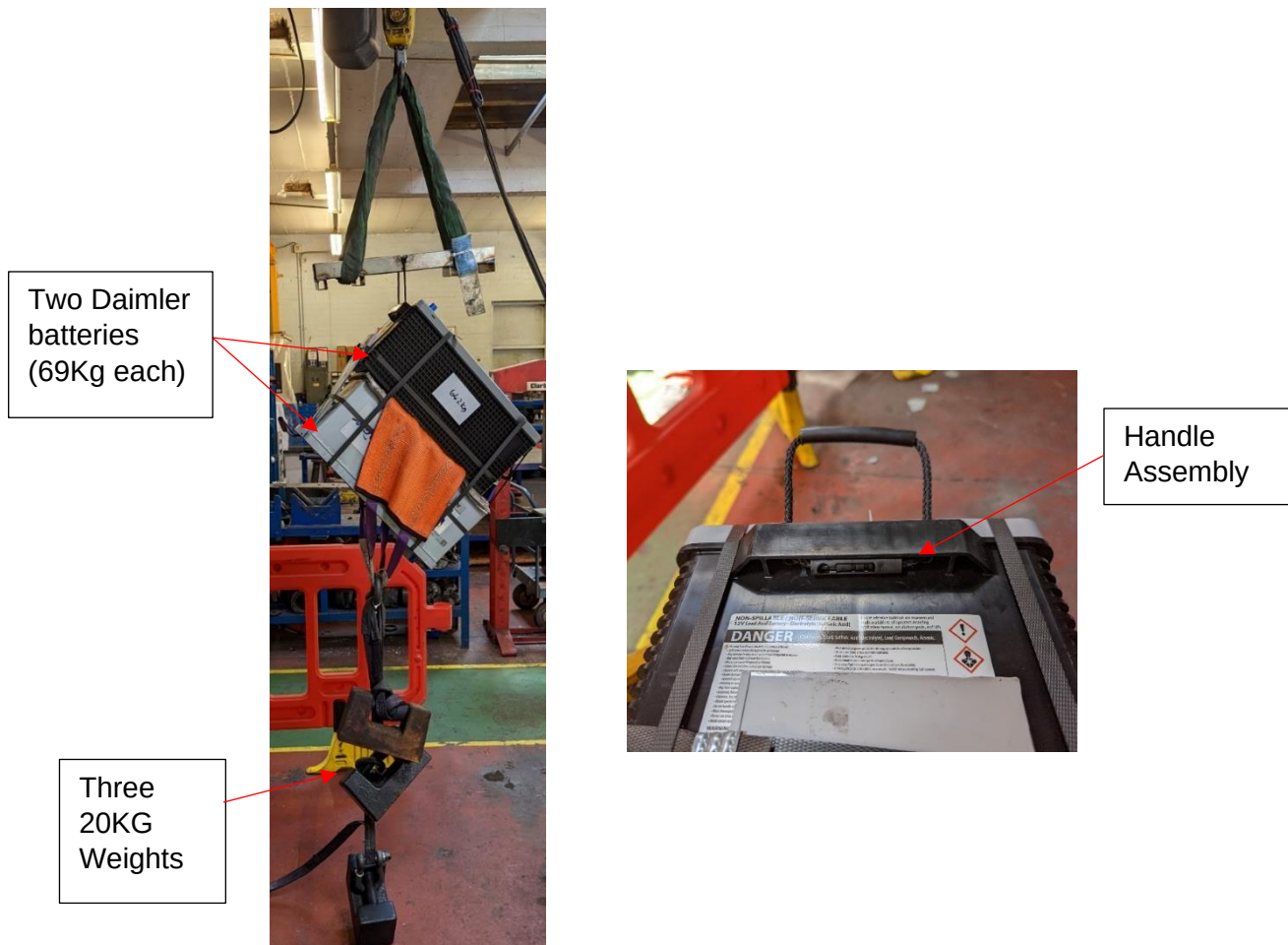


Figure 32 Newport Physical Testing of Factor of Safety of 3 Test Set-Up

The test shown in Figure 32 was carried out at EnerSys Newport to determine the allowable standard for a deviation request and validate the calculations performed regarding the tensile strength of the full assembly and the results obtained from testing the locking mechanism. Currently, referring to Figure 30, the minimum load a sample withstood at the locking mechanism with the new handles is 600N, meaning that, worst case, the maximum load it can withstand is 1920N ($600 \times 1.6 \times 2$).

A handle is installed into a standard Daimler fully formed battery. The set-up of this test consists of 2 fully formed Daimler batteries with some lead plates in between them to act as a barrier and 3 x 20 kg weights. The two batteries and lead plates represent a factor of safety of 2.16, and each 20 kg weight adds 0.3 to the factor of safety, resulting in a factor of safety of 3.07. Based on experimental results for the locking mechanism (Figure 30), most samples should pass, with some samples failing below a factor of safety of 3.07 (minimum result = 1920N = factor of safety of 2.84), which is during the lifting of the final 20 kg weight.

9.0 Results and Analysis - EnerSys Newport Testing (Factor of safety of 3 physical test)

9.1 Test Results of Currently Supplied samples (currently supplied handles)

All parts used in test were pre weighed on calibrated scales (weight was checked with a load cell during testing)												
Sample Number	Imp. Number	SF 2.16	SF 2.45	SF 2.77	SF 3.07	Photographs of Locking Feature Post Test	Notes	Edges must be Fully Formed	No Loose or Displaced Strands	Exposed Strands in Slots must not exceed 40% of total Surface Area	Exposed Strands at Dia 7.4mm must not exceed 40% of total Surface Area	
		149Kg	169Kg	191Kg	212Kg							
		1461N	1657N	1873N	2079N							
New Handles												
1	4	PASS	PASS	PASS	FAIL		Sample held SF 3.07 for 10 seconds then failed at End	X	X	X	X	
2	6	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
3	5	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
4	5	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
5	5	PASS	PASS	PASS	FAIL		Failed at End Moulding	X	X	X	X	
6	7	PASS	PASS	PASS	FAIL		End Moulding displaced	X	✓	X	X	
7	2	PASS	PASS	PASS	FAIL		Failed at End Moulding	X	✓	X	X	
8	4	PASS	PASS	PASS	PASS			✓	✓	X	✓	
9	3	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
10	4	PASS	PASS	PASS	PASS		White stress mark present on plastic housing	✓	✓	✓	✓	
11	7	PASS	PASS	PASS	FAIL		Failed at End Moulding	X	✓	X	X	
12	2	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
13	5	PASS	PASS	PASS	PASS			X	✓	✓	✓	
14	7	PASS	PASS	PASS	FAIL		Failed at End Moulding	X	✓	X	X	
15	8	PASS	PASS	PASS	PASS			✓	✓	X	✓	
16	4	PASS	PASS	PASS	PASS			✓	✓	✓	✓	
17	5	PASS	PASS	PASS	PASS			X	✓	X	✓	
18	8	PASS	PASS	PASS	PASS			X	✓	X	X	
19	7	PASS	PASS	PASS	PASS			✓	✓	X	✓	
20	3	PASS	PASS	PASS	PASS			✓	✓	X	✓	
30% Failure rate												

Figure 33 Newport Physical Testing of Factor of Safety of 3 Test Results for New Rope (5.5mm Diameter)

As expected, the minimum value that the samples comply with is between 1873-2079N (see Figure 33), which aligns with the minimum obtained result from testing the locking mechanism (600N, which is equivalent to 1920N). The point at which each sample failed (7 samples that failed) was between a factor of safety of 2.77 and 3.07; these samples failed while lifting the final 20 kg weight, not before. Most samples withstood a factor of safety of 3 (70% pass rate).

Figure 44 shows examples of samples not passing the checklist shown to the right of the "notes" in Figures 33 & 37.

9.2 Failure modes

All failures occurred at the end moulding. There were two failure types, failure mode 1, which occurred in 5 samples and failure mode 2, which occurred in 1 sample (see Figures 34 & 35).

Sample 1 – Failure mode 1 – End moulding displaced from locking mechanism



Figure 34 Sample 1 - Failure Mode 1 - Newport Physical Testing

Sample 6 – Failure mode 2 – Rope displaced from end moulding



Figure 35 Sample 6 - Failure Mode 2 - Newport Physical Testing

Sample six's unique failure mode can be attributed to some edges not being fully formed. There were many exposed strands across the entire end moulding, leading to a weak connection between the rope and plastic, ultimately leading to the rope becoming dislodged (see Figure 36 for sample 6 image before testing).

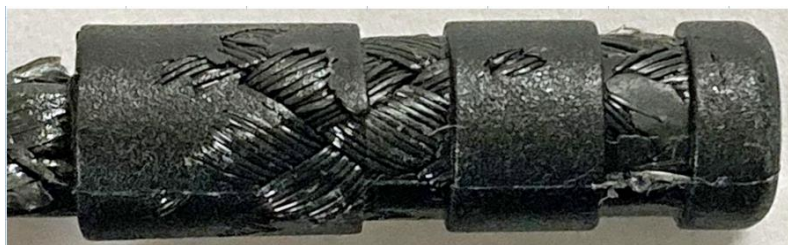


Figure 36 Sample 6 image prior to physical testing

9.3 Test Results of Previously Supplied samples (previously supplied handles)

All parts used in test were pre weighed on calibrated scales (weight was checked with a load cell during testing)												
	Sample Number	Imp. Number	SF 2.16	SF 2.45	SF 2.77	SF 3.07	Photographs of Locking Feature Post Test	Notes	Edges must be Fully Formed	No Loose or Displaced Strands	Exposed Strands in Slots must not exceed 40% of total Surface Area	Exposed Strands at Dia 7.4mm must not exceed 40% of total Surface Area
			149Kg	169Kg	191Kg	212Kg						
			1461N	1657N	1873N	2079N						
	Previously Supplied Handles											
	1	4	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	2	5	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	3	7	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	4	2	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	5	3	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	6	4	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	7	8	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	8	1	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	9	1	PASS	PASS	PASS	PASS			✓	✓	✓	✓
	10	1	PASS	PASS	PASS	PASS			✓	✓	✓	✓

Figure 37 Newport Physical Testing of Factor of Safety of 3 Test Results for Old Rope (5.0mm Diameter)

The results from Figure 37 show that the originally supplied handles comply with a factor of safety of 3, as expected. A larger sample size would be preferable, but only ten samples were available for testing. These results align with the minimum obtained result from testing the locking mechanism (878N, which is equivalent to a vertical load of 2810N) (refer to Figure 31).

10.0 Methodology - Root Cause Analysis

The results of the physical testing performed at EnerSys Newport align with what is seen during the locking mechanism test proposed in section 6.0. Therefore validating this test method.

Now that the current factor of safety has been determined (2.77 minimum), a baseline has been established for an allowable deviation. It is important to use the data gathered to determine the root cause. From testing, it can be seen that all failures occur at the locking mechanism, more precisely, the end moulding where there is variation in mould quality.

Initially, the only information available regarding this issue was that the currently supplied handles exhibit lower tensile strength than previous batches, and visually there is an overmoulding issue at the end moulding.

Initial research was performed on what can cause overmoulding in injection moulded products. A fishbone/cause and effect diagram was created by Awais Ahmed and discussed with the supplier, which helped the team understand and reach a consensus on the most likely cause of the overmoulding issue.

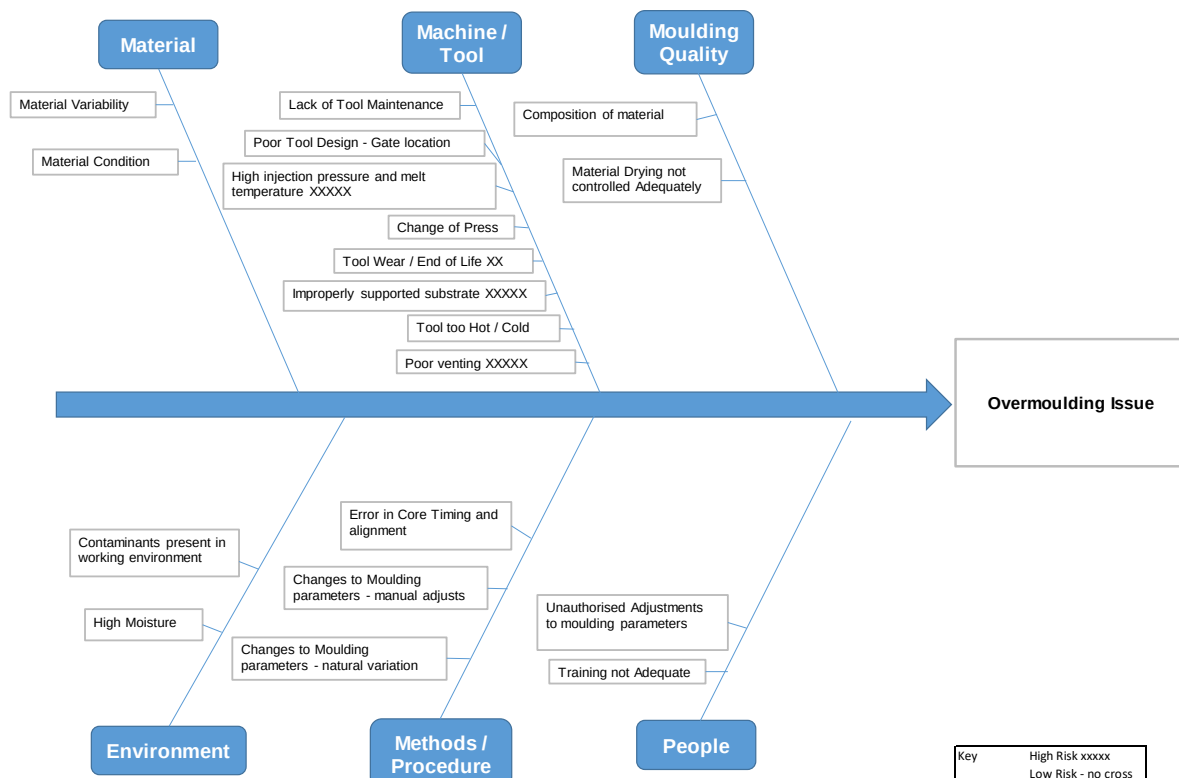


Figure 38 Fishbone Diagram of potential causes of Overmoulding Issue

10.1 Main possible Contributors to Overmoulding from Research

Too high injection pressure increases the likelihood of plastic deformation (Zetar, 2022).

Too high a mould temperature leads to a thin resin that will not correctly fill the mould (Seoteam, 2021).

Cooling time is too short; this will cause the end moulding not to be fully formed (GLS, 2005).

Flow Path Design is not appropriate. For example, the plastic does not mould uniformly around the rope due to the flow path affecting travel time to each area of the rope (Avient, 2020).

The gate design can cause overmoulding. This is the point at which plastic flows through the mould. It is good practice for gates to be located at the thickest walls as positioning them at thin walls will generally cause overmoulding (GLS, 2005).

If there is inadequate or improper lubrication, it can cause overmoulding around the rope, as it will affect the adhesion of the plastic to the rope (Avient, 2020).

This issue has been experienced before due to the hot runners not correctly adjusting the flow of material into every cavity (see section 14.0 for additional information).

10.2 Meeting Takeaway

After the discussion, it was found that this is not a processing issue as the supplier has confirmed that there were no changes in processing conditions or the process itself; however, they mentioned that they have had to outsource a new rope due to supply issues; therefore, an analysis on the new rope has become the subject of the root cause analysis.

11.0 Results and Analysis - Root Cause - Comparison of Rope Thickness

The meeting regarding the root cause with the supplier resulted in the supplier claiming that they had to outsource a new rope due to supply issues (section 10.2). This information now points the root cause analysis in the direction of the newly supplied rope being the issue.

The root cause analysis will focus on the differences between the previously supplied and currently supplied ropes.

11.1 Thickness of Old Rope



Figure 39 Measurements of Rope Diameter (old rope)

11.2 Thickness and quality of New Rope

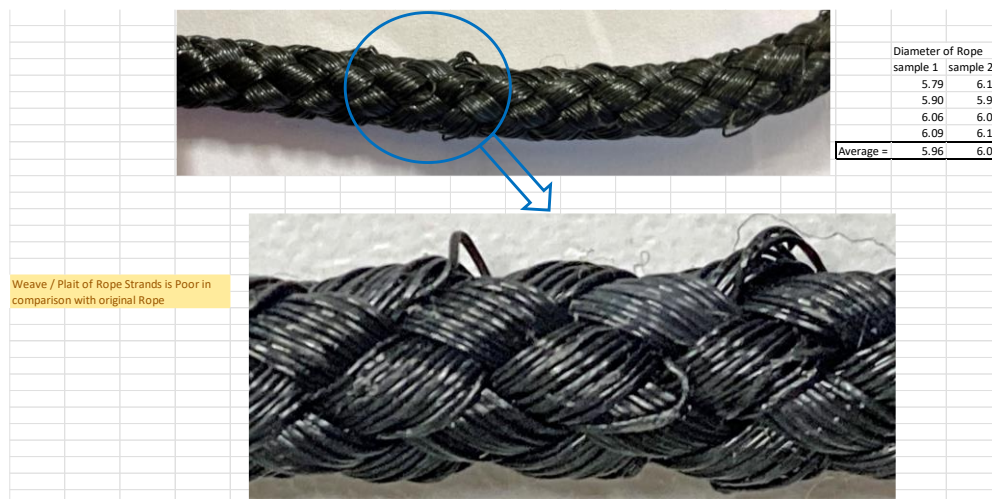


Figure 40 Measurements of Rope Diameter (new rope)

The new ropes that have been supplied have a diameter that is, on average, 0.6mm larger than the originally supplied rope (see Figures 39 & 40). It can be determined that this leads to an overmoulding issue where there is a larger amount of exposed strand around the end moulding of the plastic moulding, as a larger rope diameter leads to less plastic surrounding the rope (refer to section 12.0). Note that the thicknesses were taken around the whole diameter of the rope using a quick image machine.

11.3 Exposed Strands

Exposed strands cause issues such as a decrease in strength due to the reduced thickness of the plastic surrounding the rope and can cause edges of the plastic grooves not to be fully formed, which will also significantly reduce the strength of the part as it allows twist deformation under loading which will dislodge the end moulding from the locking mechanism (see Figure 41 for examples). Exposed strands are significantly more pronounced with handles that use the new rope (see Figures 42 & 43).

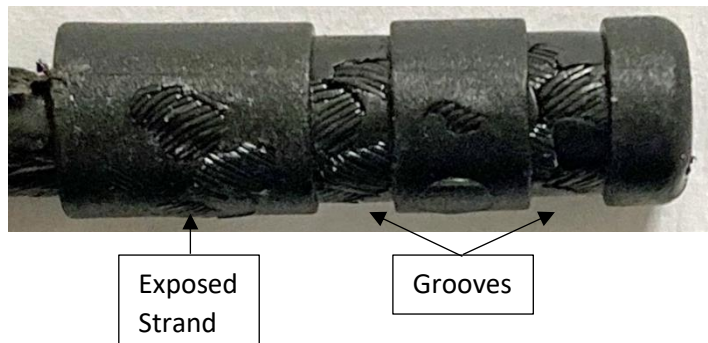


Figure 41 Image showing Overmoulding Issue at end moulding (new rope)

12.0 Results and Analysis - Root Cause - Thickness at Grooves Comparison

A difference in the thickness of the ropes has been confirmed (see section 11.0); it is essential to measure the thickness at the grooves to determine the thickness of the plastic at these locations, as this is the weakest point of the end moulding and is most susceptible to bend twist deformation during loading.

12.1 Originally supplied Handles (old rope)

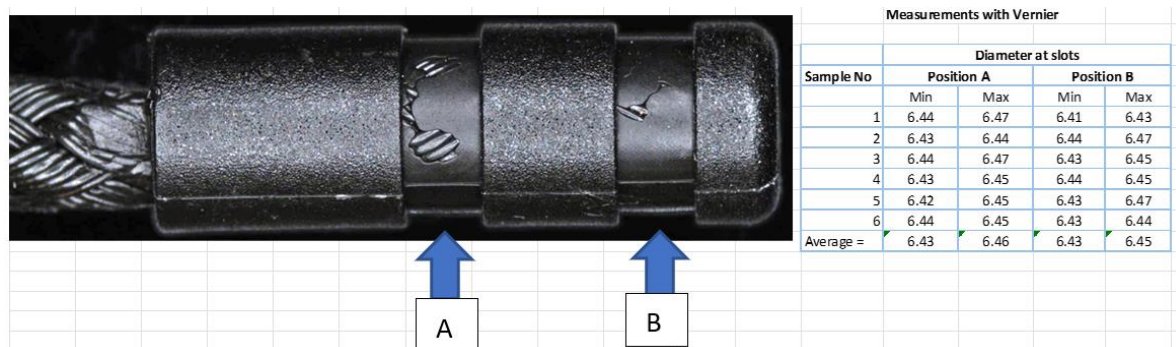


Figure 42 Diameter at Slots of End Moulding (Old Rope)

12.2 Currently Supplied Handles (new rope)

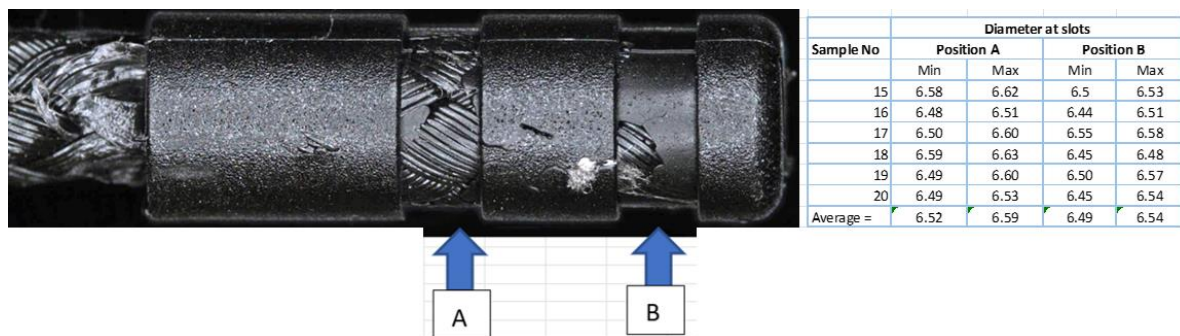


Figure 43 Diameter at Slots of End Moulding (New Rope)

The thickness results from Figures 42 & 43 show an average of 0.1mm difference in diameter at the grooves where the currently supplied rope (new rope) is 0.1mm larger. This means that there is approximately a 0.5mm decrease in the thickness of the plastic at these points as the new rope is, on average, 0.6mm larger (refer to figures 39 & 40), meaning it will take a reduced amount of stress at these areas before failure occurs.

13.0 Results and Analysis - Root Cause - Stress Analysis of End Moulding Sections

Hand calculations are performed to determine the difference in the amount of stress each section of the end moulding can withstand to understand further how the difference in rope thickness affects the part's strength.

The stress calculations shown in Figure 44 highlight the importance of controlling the quality of the moulding. It shows a decrease in the stress that the part can withstand at the three highlight sections for the new rope.

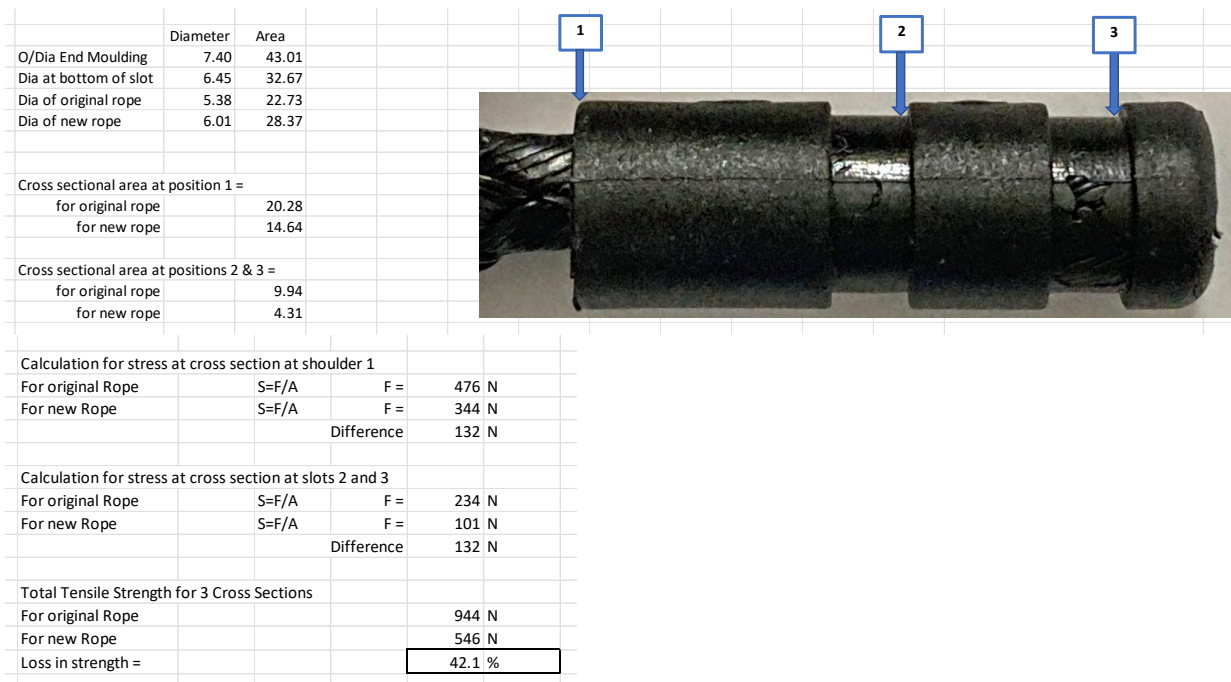


Figure 44 Stress Calculations at each end moulding section

A 42% loss in strength and lower thickness of plastic at the grooves of the end moulding gives sufficient evidence that the root cause of this decrease in strength at the locking mechanism can be attributed to the new rope being a larger diameter than the originally supplied rope. As there is a lot of variation in the quality of the end moulding, the following steps to consider are to produce a quality control criteria and determine if any changes in design can be made or what alternative solutions there are to resolve this issue.

14.0 Design Constraints

Now that the root cause has been determined, it is important to discuss the design constraints of the part to establish steps towards eliminating the issue.

The first potential solution would be to increase the thickness of the plastic surrounding the rope to ensure that there is no overmoulding and to improve the part's strength. This, however, would not be possible due to the design of the handle assembly. An increase in the thickness of the end moulding would need a resultant increase in the cavity size and depth of the locking mechanism. The diameter that the end moulding must be fed through to be assembled onto a battery is only 0.1mm larger (tight fit refer to Figure 45), meaning an increase in the thickness of the end moulding will result in the part not fitting into the battery.

The design of the battery cannot be altered at all as the product will need to undergo recertification, which will incur significant costs and take months to perform.

Due to supply chain issues, the old rope cannot be sourced, so the current supplier will actively look for alternatives of the same diameter to approve.

Currently, the only viable solution would be to look for alternative suppliers and seek alternative designs. The currently supplied samples will need to be used under a deviation request. Developing quality control criteria is essential to ensure that sample quality is controlled and variation is limited.

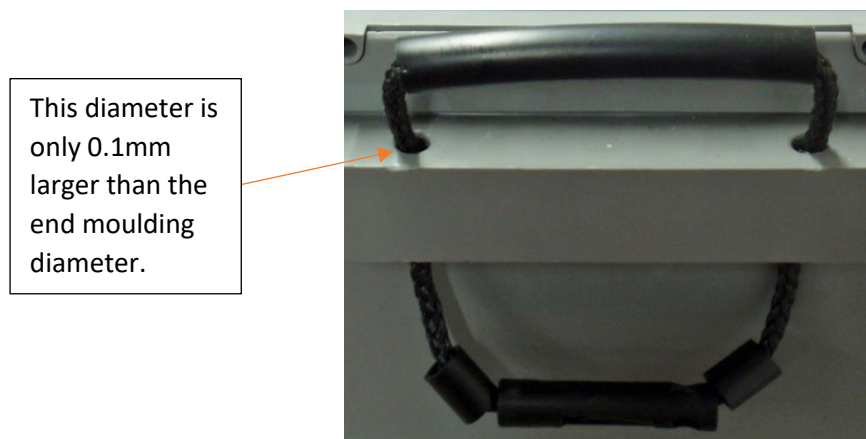


Figure 45 Assembly of Handle into Battery frontal view

Table 4 shows images from a report created at EnerSys, where a similar issue was observed with another product type. Unfortunately, the solution to that issue cannot be implemented as it was a moulding tool modification where the hot runners were replaced (EnerSys, 2016). In this case, the issue does not lie within the moulding tool but the rope used. However, the quality control criteria used for the previous issue can be implemented in this case.

15.0 Quality Control Document

A screening procedure was developed to ensure that the quality of the parts are consistent and will meet the set-out requirements in the deviation request (refer to section 16.1 & 16.2); all samples must be screened to the quality standard shown in Figure 46.

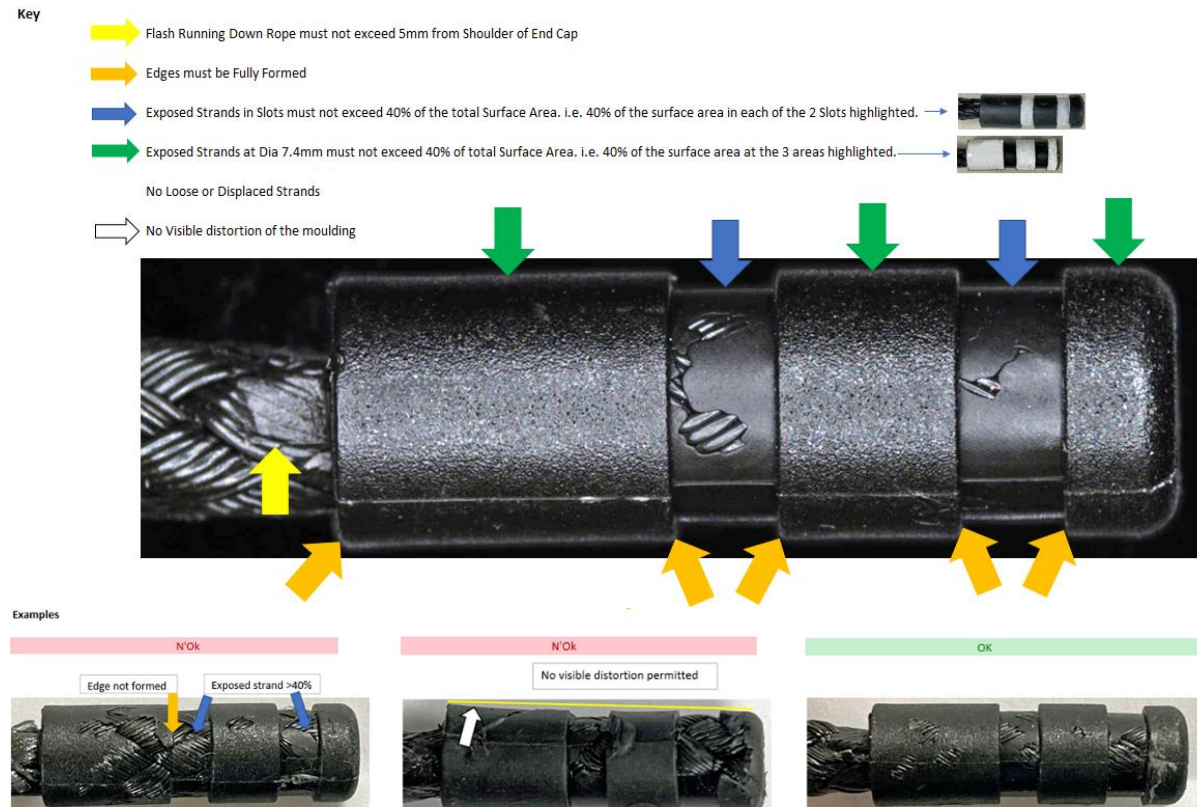


Figure 46 Quality Control Criteria

The flash running down the rope criteria is a general criterion for products that use rope handles at EnerSys. It ensures that there are no issues with the fit of the part.

Edges must all be fully formed as they are vital to the part's structural integrity; they combat against bend twist deformation and reduce the likelihood of the end moulding from displacing from the cavity.

The 40% exposed strand criteria, as explained in section 14.0, was taken from historical data for another product type that was facing a similar issue. As this issue is similar to what has been seen in the past at EnerSys and this criteria was previously approved, it will also be implemented in this case. The aim of this is to reduce the likelihood of the rope twisting and becoming dislodged from the plastic casing. Exposed strands will reduce the rigidity of the part and lead to a weaker bond between the rope and plastic.

15.0 Quality Control Document

Although a supplier visit has not been made, injection moulding involves a metal jig split into two parts with a symmetrical shape of a desired moulding which would then be clamped together. Plastic is injected into the jig, and on the release of the jig, a plastic moulding will be created. In this case, each end of the rope will be inserted into a jig; plastic will be injected, resulting in moulding the rope handle (Star Rapid, 2021).

Flash is where the plastic extends beyond the pip and is on the rope itself. This is likely due to the high temperature during the plastic injection when the rope is inserted into the jig. Some excess plastic will flow around the flat piece of rope at the yellow arrow in Figure 46 as the jig clamps onto it.

15.1 Reasons for choosing this method of quality control

This method will help control the quality of the products being put through, as any products that do not comply will be rejected. This will possibly improve the baseline performance of the product by filtering out “bad product”, which will improve the capability of the results seen.

It can be carried out quickly and without expensive equipment or specialized training. This helps streamline production processes and reduce the time and costs associated with quality control (TXNDT, 2019).

Visual inspections will help ensure compliance with the relevant regulations and prevent costly fines or legal issues (TXNDT, 2019).

The main disadvantage is the misinterpretation of flaws from person to person and that generally, only large flaws are noticeable (TXNDT, 2019). The main issue, in this case, is the 40% exposed strand requirement, but this should not be such an issue if a person passes a product through that is marginally over that value.

15.2 40% requirement of quality criteria document

As explained in sections 14.0 and 15.0, the 40% exposed strand requirements are based on research into previous issues that EnerSys has had with handle mouldings for another product type. Table 4 shows the set criteria, and Figure 47 gives a more in-depth criterion.

FAULT – LOOSE / EXPOSED STRANDS AT END CAP MOULDING		
Acceptable Standard	Not Acceptable	Acceptance criteria
	 Percentage of Loose Strands must not exceed 40%	Loose Strands cause a problem on assembly.

Table 4 Example of use of exposed strand criteria for a rope used on another product type (Historical Criteria) (EnerSys, 2016)

15.2 40% requirement of quality criteria document

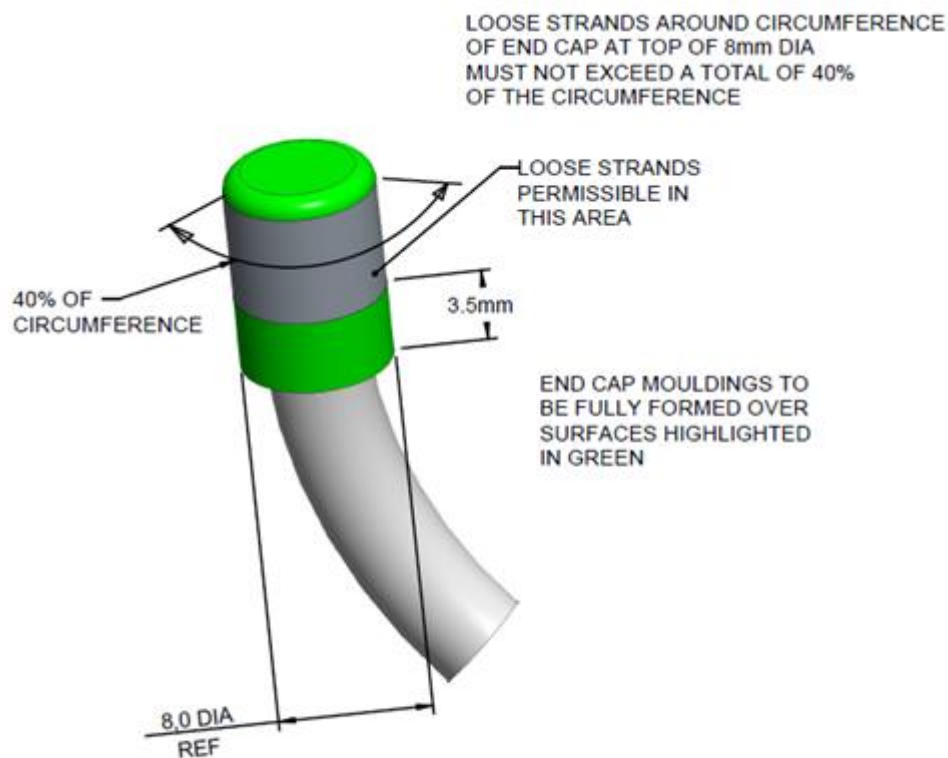


Figure 47 Example of use of exposed strand criteria for a rope used on another product type (Historical Criteria) (EnerSys, 2016)

This is a subjective pass or fail standard, which comes with the disadvantage of how an operator will perceive the level of exposed strands present.

This issue was resolved in the past by replacing the hot runner's injectors to better adjust the flow of material in every cavity (EnerSys 2016). However, as explained in section 14.0, this will not work with the present problem.

16.0 Recommended actions based on Results and Analysis performed in previous sections Sept-22

Based on the information gathered in this report's previous sections, the recommended actions below were communicated to the supplier and EnerSys France.

16.1 Set the load requirements for the Handle as follows

For Testing on Rope and Plastics Test Fixture in Battery Orientation - requirement is 1873N (191Kg /421 lbs), this equates to a Safety Factor of 2.77.

For Testing the Locking Mechanism on Straight-line pull test - requirement- Handle must withstand a load of 600N (61.2Kg /135 lbs) this equates to a Safety Factor of 2.8.

Design authority to confirm agreement with these loads.

16.2 Deviation for Batch of 40,000 supplied Handles with following conditions

EnerSys France Testing of Samples from this batch meets the requirements of the Daimler specification.

The End Mouldings are 100% inspected prior to fitment to battery - refer to quality criteria document (section 15.0).

100% Check needs to continue until:-

- Rope & Plastics have replaced the rope, or
- Rope & Plastics have modified the Handle or
- an alternative supplier has been found.

16.3 Instructions for Rope & Plastics (supplier)

Source a replacement Rope. The quality of the weave / plait on samples from the batch of 40,000 is poor - refer to Figure 40.

The diameter of the new rope is too big for the End Moulding - refer to sections 11.0 & 12.0 for Inspection details and section 13.0 for Stress Calculations.

Conduct 100% Inspection on any future batches manufactured with respect to End Mouldings - Visual Standard (until the Rope is replaced).

Continue Load Testing in both Battery orientation and Straight Line pull test across Locking Mechanism (use 1873N and 600N Load as detailed above).

17.0 Results and Analysis - Screening Method performed at EnerSys

As per the recommended actions (section 16.0), 100% screening of samples was initially performed at EnerSys France and any related costs were initially paid for by the supplier.

Shipment Detail	Ship Qty (pcs)	Inventory Location	Screening Result (Reject, pcs)	Remark	Disposition
Arrive at Arras on 19-May	40,500	Arras Plant	10,747	Failure Rate: ~27% (not screened at supplier)	Pending R&P reply
Arrive at Arras on 7-Sep	31,500	Arras Plant	13,179	Failure Rate: ~42% (not screened at supplier)	Pending R&P reply
N/A	22,500	R&P US	N/A	N/A	N/A
29-Sep-2022	21,000	R&P US	N/A	Screening Method verified at supplier on 14-Sep	N/A

Figure 48 Initial Screening Details (performed at EnerSys France)

As shown in Figure 48, there is a large failure rate when comparing the samples to the screening requirements. The costs for the first two batches can be seen in Figure 49; there is a significant amount of money involved in the rejection of samples and 'sorting' through the screening method and therefore, if possible, an alternative design or sourcing a rope with a similar diameter to what was previously supplied is the main priority to avoid these costs.

Part#	Order#	Received Quantity (pc)	NC Quantity (pc)	NC Cost (€)	Sorting cost (€)	Air Freight (€)	Total Cost (€)
10HAN0029	4501472245	40500	10747	4298.8	3639.5	3050	18844.9
10HAN0029	4501455997	31500	13197	5271.6		2585	
Total		72000	23944	9570.4	3639.5	5635	18844.9

Figure 49 Screening Costs

To reduce the impact of waste on the environment, any samples the supplier has rejected will be reused by selling to other customers with lower requirements than EnerSys.

18.0 Results and Analysis - Screening at supplier non-compliance issue

After the supplier agreed with EnerSys's screening method, they decided to screen the samples themselves. EnerSys France screened the samples after the supplier had screened them to ensure that the supplier complies with the quality criteria correctly.

Table 5 shows the percentage of samples that conform to and do not conform to the screening requirements based on screening performed at EnerSys France after being screened at the supplier.

	Quantity checked	NOT CONFORM (NC)	% NC	CONFORM (C)	% C
26-oct	3000	9	0,30	2991	99,70
27-oct	3000	4	0,13	2996	99,87
31-oct	9000	31	0,34	8969	99,66
04-nov	6000	15	0,25	5985	99,75
07-nov	1500	67	4,47	1433	95,53
07-nov	1500	1407	93,80	93	6,20
08-nov	4500	1527	33,93	2973	66,07
09-nov	4500	1233	27,40	3267	72,60
10-nov	4500	83	1,84	4417	98,16
14-nov	6000	138	2,30	5862	97,70
Total	43500	4514	10,38	38986	89,62

Table 5 Screening Data of Samples that conform to EnerSys Quality control criteria after being screened initially by the supplier then checked again at EnerSys

Testing carried out from 26 Oct to 04 Nov are post the new screening process, and as is noted, %NC is below 1%. The main issue is that “bad” rejections remain even after the supplier has 100% screened the samples. If the samples marginally failed due to the percentage of exposed strands, this would not be a large issue; however, samples like those shown in Figure 50 are being observed.



Figure 50 Example of 'Bad Samples' picked out after supplier screening during EnerSys screening

It should be further noted that after some investigation in regards to the failure rate on the handles tested between 07 Nov – 14 Nov, it was found that the consignment EnerSys received was in error; the cartons loaded from EnerSys' facility in the US were not consigned and as such had not been through pre-screening. Processes have been tightened across all hubs to ensure that only pre-screened handles are delivered; as can be seen, once pre-screening has been carried out, the rejection rate fall to less than 1%.

18.0 Results and Analysis - Screening at supplier non-compliance issue

The screening requirement is now an embedded process, and the supplier screens all shipments to EnerSys and the packaging is marked accordingly.

EnerSys continue to screen the samples after the supplier as the "bad" rejections are a high risk if used by customers. However, supplier coverage of screening costs for screening performed at EnerSys France stopped after the supplier started to perform screening.

19.0 Results and Analysis - Validation of Screening Method

Thirty samples were tested post-screening at EnerSys Newport to compare to the results obtained before the screening process was implemented to determine whether sample screening positively impacts the observed strength of the part.

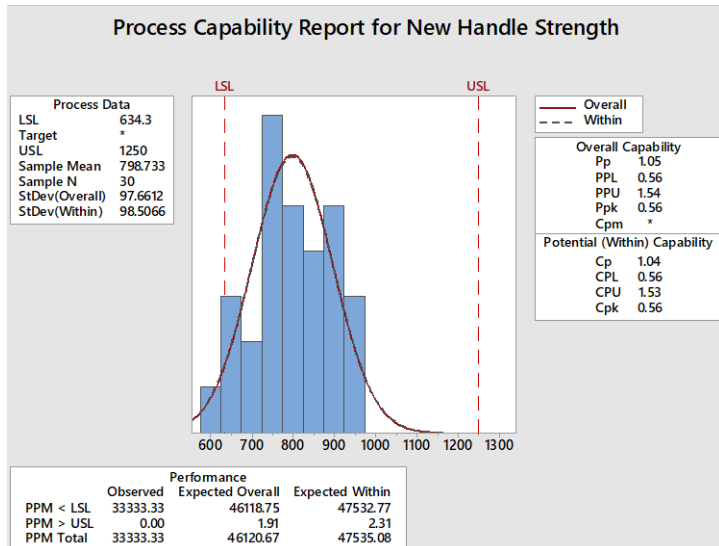


Figure 30 Capability Study of Locking Mechanism Test Results for the New Rope (5.5mm Diameter Rope)

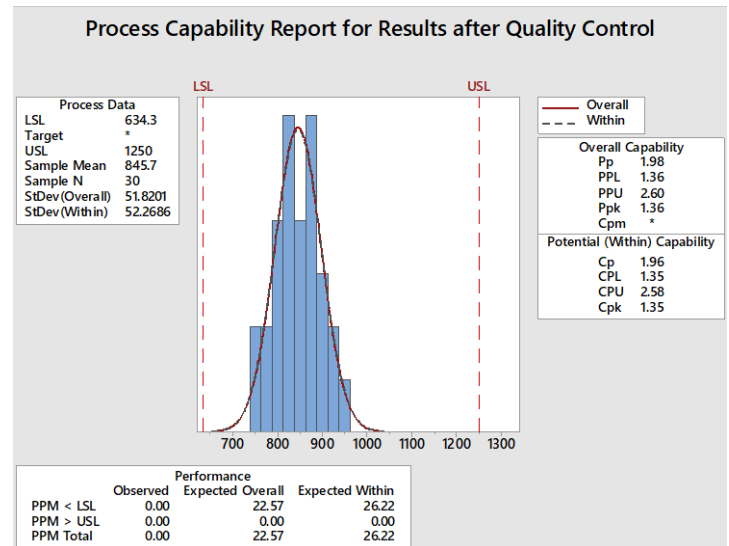


Figure 51 Capability Study of Locking Mechanism Test Results for the New Rope (5.5mm Diameter Rope) Post Screening to EnerSys Quality Criteria

The results shown in Figures 30 & 51 indicate that the implemented screening procedure positively impacts the results obtained for the handle strength. The Cpk and Ppk value improved from 0.56 to 1.36, indicating that the process in the short and long term is capable post sample screening (Hachmöller, 2022). The results show that the screening method effectively filters out the low-performing samples shown in Figure 30, as the minimum load withstood has increased from 600N to 794N (factor of safety of 3.76) post-screening. Many industries, such as EnerSys, use 1.33 as a benchmark value for CpK and Ppk to determine if a process is capable (Minitab, 2017).

See Appendix A, Figure 72 for raw data covering Figure 30. See Appendix A Table 10 for raw data covering Figure 51.

Raw data is unavailable; however, EnerSys France has informed EnerSys Newport that testing at -30&50°C was performed, and the results were above a factor of safety of 3.

20.0 Project objectives as of December 2022

Rope and Plastics are looking at multiple rope suppliers.

EnerSys are looking at a completely new supplier.

EnerSys to assess a new design of the handle proposed by LER (alternative supplier).

20.1 Current actions after meeting 02/12/22

Following a meeting this afternoon, here are the actions that need to be continued to get out of the fragile situation with Rope and Plastics (current supplier):

- Continuing the work with Rope & Plastics (current supplier) to get a robust solution that does not need any screening at the incoming inspection.
- Suggestion to do AQL for the next incoming batches, to take into consideration by the EnerSys France team.
- Accuma (alternative supplier) has proposed creating a new design for a handle which could sustain the load. However, the requirements for the drawing need to be updated by the Design Authority.
- Assess a new handle design proposed by LER (alternative supplier). One sample and a Solidworks model will be sent to the EnerSys Newport team for assessment.

20.2 January 2023 – April 2023

EnerSys is awaiting prototype designs from Accuma (alternative supplier) and new samples using alternative rope suppliers from the current supplier; however, these have not been obtained as the project has been put on hold due to a change in project priority. The next stage of the project is to perform a preliminary analysis of the LER (alternative supplier) prototype design and assess the single prototype sample that has been provided.

21.0 Methodology - Structural Analysis of LER Prototype Design

LER is an approved alternative supplier located in France. LER created a prototype design and provided EnerSys with a Solidworks model and one physical prototype produced using a 3D printer for preliminary assessment.

An acronym known as SIMPLE was used as a basis to produce the finite element model. SIMPLE involves the best practices to produce an accurate and reliable FE model and is described in this section.

21.1 Split

Split - Selecting the appropriate type of elements. Different types of elements may be used depending on the geometry and behaviour of the system being modelled. There needs to be consideration of how the geometry is divided into small finite-sized elements ([2]Lake, n.d.).

In this case, the level of detail required is the important factor. As a preliminary analysis will be performed, a somewhat accurate and fast computational speed would be acceptable; therefore, second-order elements were used.

Second-order elements are finite elements that use polynomial shape functions of second order, compared to first-order elements, which use shape functions of first order (Webster, 2021).

21.1.1 Advantages of Second order elements

Second-order elements provide higher accuracy than first-order elements, especially for problems with curved or complex geometries (Webster, 2021).

As second-order elements have mid-side nodes, they are much better than first-order for capturing the curvature of an object and deformation (DesiGn HuB, 2019).

21.1.2 Disadvantages of second order elements

The higher accuracy of second-order elements comes at the cost of increased computational cost in terms of time and memory required to solve the equations (Webster, 2021).

Second-order elements can be more sensitive to mesh quality than first-order elements as many more nodes are taken, so more care must be taken in meshing to ensure that the elements are of good quality.

Third-order elements are more accurate and produce clearer deformation results than second-order elements, which is better for more complex systems (Wai et al., 2013). In this case, the model wants to be kept as simple as possible, as this is a preliminary analysis.

21.2 Interpret

Interpret - The next step is interpreting the physical problem and applying appropriate boundary conditions to the model. The type of problem being simulated needs to be considered (e.g., static or dynamic), the type of loads and boundary conditions (e.g., forces, displacements, or temperature gradients), and the physical environment in which the problem occurs ([2]Lake, n.d.).

In this case, the boundary conditions involved trying to simulate a hand lifting a handle with a load of 3 batteries being applied to specific sections.

21.3 Material Properties

Material properties - In this step, the material properties of the elements used in the model need to be considered. This includes determining the appropriate material model to use (e.g., linear or nonlinear), defining the material properties (e.g., Young's modulus and Poisson's ratio), and accounting for any anisotropic behaviour of the material ([2]Lake, n.d.).

In this case, the material properties for the actual production material were readily available; however, the properties for the 3-d printed model that was provided needed to be obtained from secondary data.

The mechanical properties of polypropylene from Figures 52 & 53 are directly from the material supplier. This material will be used to produce the handles after approval of the prototype design.

Mechanical Properties		
Mechanical properties data		
Elastic modulus, 1 st principal direction [E1]	1340	MPa
Elastic modulus, 2 nd principal direction [E2]	1340	MPa
Poissons ratio [v12]	0.3920	
Poissons ratio [v23]	0.3920	
Shear modulus [G12]	481	MPa

Figure 52 Material Properties for PB150G2M Polypropylene received via email from a representative of Repsol (material supplier) (Reyes, 2023)

PROPERTIES	VALUE	UNIT	TEST METHOD
GENERAL			
Melt flow rate (230°C/ 2,16 kg)	7	g/10 min	ISO 1133
Density at 23°C	905	kg/m ³	ISO 1183

Figure 53 Material Properties for PB150G2M Polypropylene (Repsol, 2021)

Polypropylenes maximum elongation before break is between 50-145% (polymerdatabase, 2018).

The average tensile strength for polypropylene is 36MPa (Shimadzu, 2020).

21.3 Material Properties

Data for the prototype material was obtained from a degree project report for Sweden University. The project entailed performing physical tests and comparing them to another source to produce a material properties table for the prototype material (Duraform ProX PA).

In Figure 54, “ E_T, E_L is Young’s modulus, ν_{TT}, ν_{LT} is Poisson’s ratio, $\sigma_{0,2,T}, \sigma_{0,2,L}$ is the yield limit, $\sigma_{UTS,T}, \sigma_{UTS,L}$ the ultimate tensile strength and $\epsilon_{b,T}, \epsilon_{b,L}$ the elongation at break” (Lindberg, 2018). Figure 54 was derived through experimentation and updated according to new results obtained through testing and comparison of other sources (Lindberg, 2018).

Table 6 Material parameters from the combined data of the first and second material test and the results from the initial material test

Parameter	Updated value	Initial value
E_T [MPa]	1600	1510
E_L [MPa]	1780	1770
ν_{TT} [-]	0.4	0.4
ν_{LT} [-]	0.4	0.4
G_{TT} [MPa]	570	540
G_{LT} [MPa]	600	580
σ_{Ts} [MPa]	19.5	17.7
σ_{Ls} [MPa]	21.2	20.9
τ_{TTs} [MPa]	11.0	9.7
τ_{LTs} [MPa]	16.3	11.1
$\sigma_{UTS,T}$ [MPa]	33.7	30.5
$\sigma_{UTS,L}$ [MPa]	30.0	30.6
σ_0 [MPa]	19.5	-
n [-]	0.35	-
F [-]	0.58	0.64
G [-]	0.42	0.36
H [-]	0.42	0.36
L [-]	1.57	1.66
M [-]	0.72	1.27
N [-]	0.72	1.27

Figure 54 Material Properties for Prototype Material (secondary source) (Lindberg, 2018)

SOLID MATERIAL						
METRIC	ASTM METHOD	METRIC	ENGLISH	ISO METHOD	METRIC	ENGLISH
PHYSICAL				PHYSICAL		
Color		Natural				
Sintered Part Density	ASTM D792	0.95 g/cm ³	0.034 lbs/in ³	ISO 1183	0.95 g/cm ³	0.034 lbs/in ³
24 Hour Water Absorption	ASTM D570	0.65 %	0.65 %	ISO 62	0.65 %	0.65 %
Blend Ratio - % Fresh		40%				
MECHANICAL				MECHANICAL		
Tensile Strength Ultimate	ASTM D638 Type I	48 MPa	7000 psi	ISO 37	49 MPa	7100 psi
Tensile Strength at Yield	ASTM D638 Type I	48 MPa	7000 psi	ISO 37	49 MPa	7100 psi
Tensile Modulus	ASTM D638 Type I	2100 MPa	300 ksi	ISO 37	1900 MPa	273 ksi
Elongation at Break	ASTM D638 Type I	19 %	19 %	ISO 37	17 %	17 %
Elongation at Yield	ASTM D638 Type I	13 %	13 %	ISO 37	12.3 %	12.3 %

Figure 55 Material Properties from prototype material supplier (3dsystems, 2016)

21.4 Physical Properties

Physical properties - This step involves defining the physical properties of the model, such as the density, temperature, and any other relevant properties that may affect the model's behaviour ([2]Lake, n.d.).

In this case, as the material is plastic, density is the relevant physical property.

21.5 Loading

Loading - In this step, the external loads the model will be subjected to are considered. This includes defining the loads' magnitude, direction, and distribution and accounting for any time-varying loads or load histories ([2]Lake, n.d.).

For this analysis, a load will be applied to two locations based on calculations performed in previous sections to obtain a factor of safety of 3 (refer to Figure 18).

21.6 Evaluation

Evaluation - This involves examining the stress and strain distributions, deformations, and other relevant output variables and comparing them to expected results or experimental data. It also involves the assessment of the accuracy and reliability of the results and the identification of any limitations or areas for improvement in the model ([2]Lake, n.d.).

21.7 General Views of Prototype Design

Figure 56 shows general views of a rope assembled into the prototype sample.



Figure 56 General View of Handle Prototype Design

21.8 FEA Load case

The load case used throughout the analysis is consistent and is implemented to replicate what will be seen in reality.

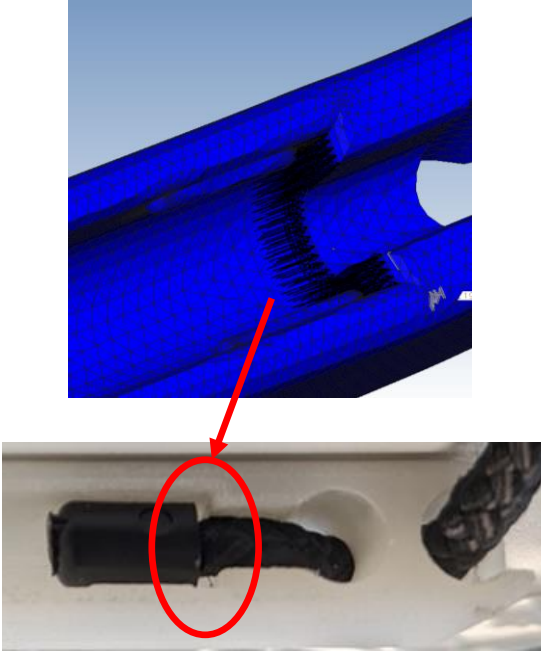
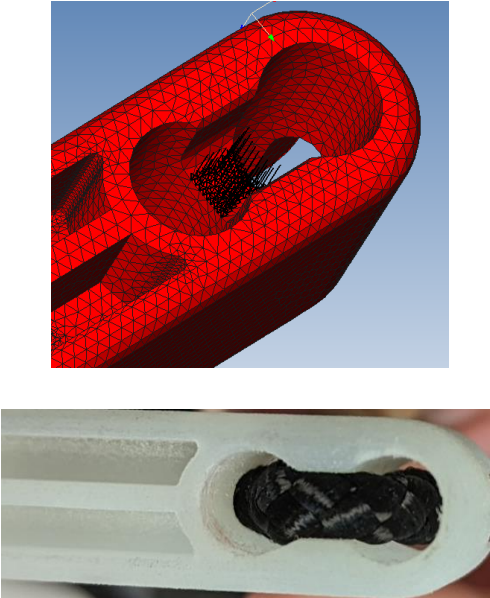
 <i>Figure 57 Horizontal Load Case</i>	Based on the factor of safety of 3 calculations (refer to Figure 18), a 634.3N load is applied horizontally to the section shown in the top image of Figure 57. The bottom image of Figure 57 shows the underside of the handle assembly, and as can be seen, if the handle is lifted, a horizontal load will be applied to the handle as the pip of the rope is pulled across the section. For simplicity, this section of the handle will be called section 1.
 <i>Figure 58 Vertical Load Case</i>	Based on the factor of safety of 3 calculations (refer to Figure 18), a 1015N load is applied vertically to the section shown in the top image of Figure 58. The bottom image of Figure 58 shows the top side of the handle assembly, and as can be seen, if the handle is lifted, a vertical load will be applied to the thin section. This section is the cause for concern in the design as it is only 3mm wide at the centre, which is a weakness in the design, especially when a load of 1000N+ is applied to this section. For simplicity, this section of the handle will be called section 2.

Table 6 FEA Load Case

21.9 FEA Constraint

Figure 59 shows that the part is constrained in all degrees of freedom at the highlighted area. This is to replicate a hand lifting the handle from underneath. In reality, a hand is not infinitely stiff, so this constraint will affect the FEA results.

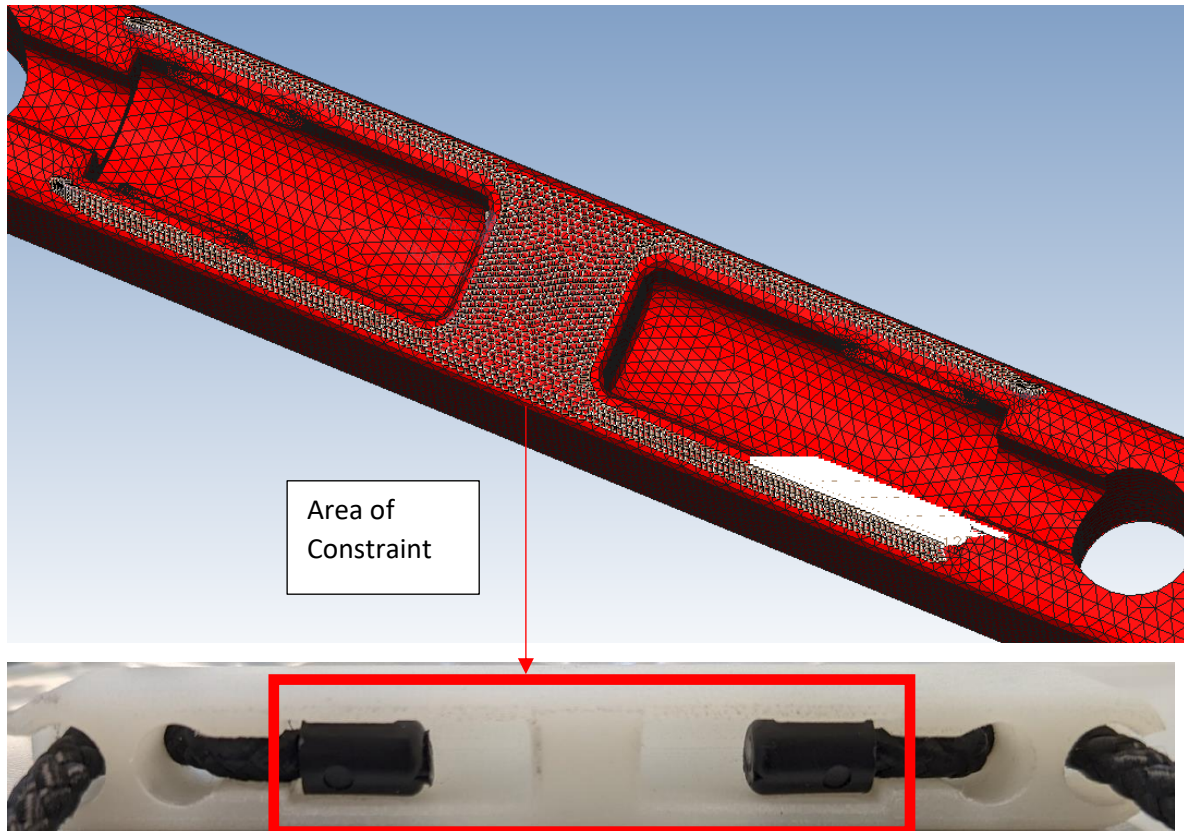


Figure 59 FEA Constraint

22.0 FEA Results and Analysis

22.1 Results for production material - Polypropylene

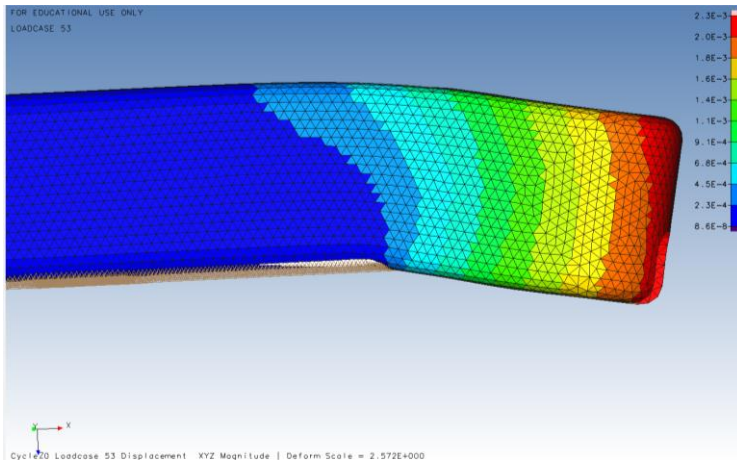


Figure 60 Deformation for Production Material

Overall height = 20mm

The maximum elongation shown in Figure 60 is 2.3mm which equates to an elongation of 11.5%.

This elongation is much lower than the 45-150% polypropylene is able to withstand, indicating that the handle will not crack due to elongation.

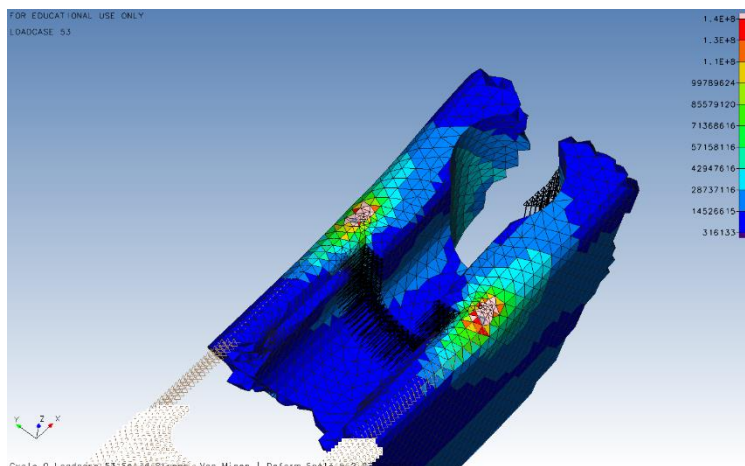


Figure 61 Stress values at Section 1 for Production Material

The stress values shown at section 1 in Figure 61 are very high, with a maximum of 140MPa.

Polypropylene has a tensile strength of approximately 36MPa. This result indicates that the part will break under stress as the stress exhibited is 389% greater than the material's tensile strength. However, due to the constraints applied, the result shown does not reflect actual reality. This will be discussed further in section 22.3.

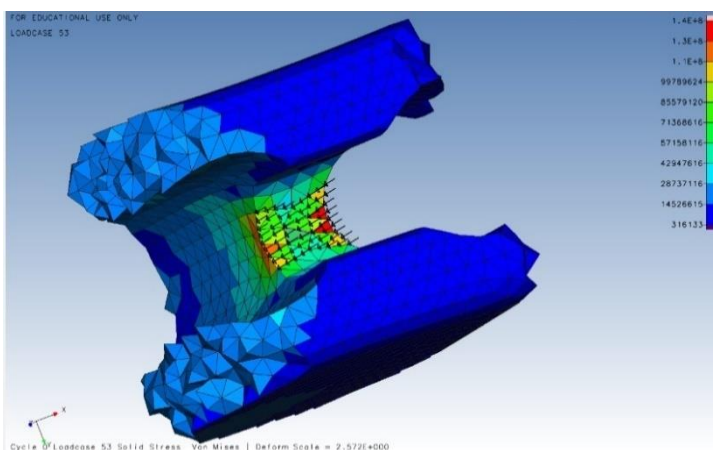


Figure 62 Stress values at Section 2 for Production Material

The stress values shown at the thin section (section 2) in Figure 62 are very high, with a maximum of 130MPa.

Polypropylene has a tensile strength of approximately 36MPa. This result indicates that the part will break under stress at the thin section as the stress exhibited is 361% greater than the material's tensile strength.

Table 7 FEA Results for Production Material

22.2 Results for prototype material - Duraform ProX

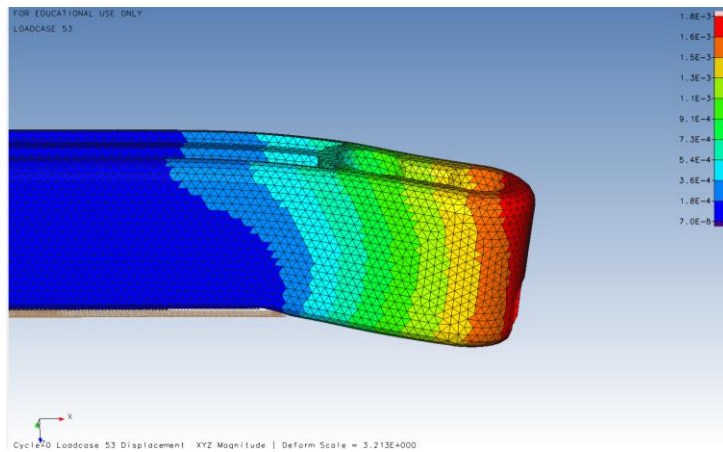


Figure 63 Deformation for Prototype Material

Overall height = 20mm

The maximum elongation shown in Figure 63 is 1.8mm which equates to an elongation of 9%.

This elongation is lower than the 19% Duraform ProX can withstand, indicating that the prototype will not crack due to elongation.

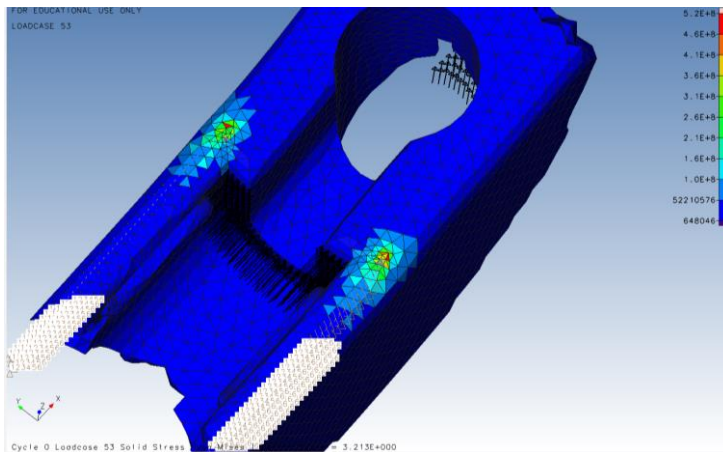


Figure 64 Stress values at Section 1 for Prototype Material

The stress values shown at section 1 in Figure 64 are very high, with a maximum of 520MPa.

Duraform ProX has a tensile strength of approximately 48MPa. This result indicates that the part will break under stress as the stress exhibited is 1083% greater than the material's tensile strength. However, due to the constraints applied, the result shown does not reflect actual reality. This will be discussed further in section 22.3.

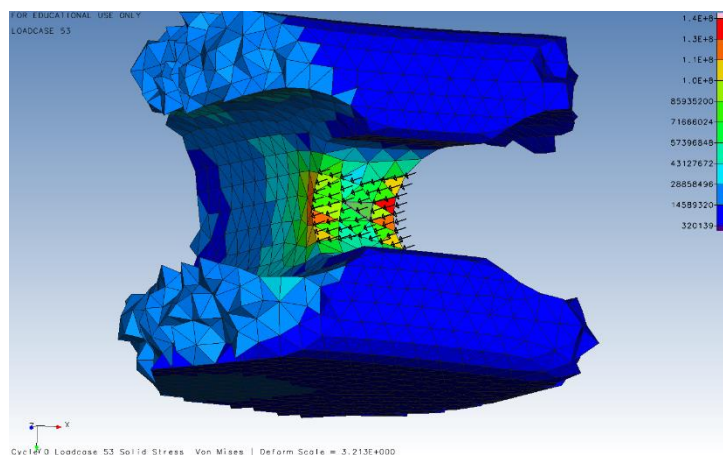


Figure 65 Stress values at Section 2 for Prototype Material

The stress values shown at the thin section (section 2) in Figure 65 are very high, with a maximum of 130MPa.

Duraform ProX has a tensile strength of approximately 48MPa. This result indicates that the part will break under stress at the thin section as the stress exhibited is 271% greater than the material's tensile strength.

Table 8 FEA Results for Prototype Material

22.3 FEA Evaluation

Based on the results of the FEA analysis, the model of the new handle cannot withstand the expected load that a factor of safety of 3 would exhibit on the part.

The main concern is the structural integrity of the thin section, as shown in Figures 62 & 65. Based on the results, this section will be the failure mode of the part in question.

Even though there is a large amount of stress on the underside of the part shown in Figures 61 & 64, this section is of no concern as the high-stress values can be attributed to SPC constraints. The SPC constraints set to simulate a hand lifting the part is not allowing the part to move in 6 degrees of freedom at the high-stress areas shown in Figures 61 & 64, which will heavily impact the stress at this section as it is trying to bend at the edge of the constraint. In reality, the part will deform at the centre of the handle as a hand is not infinitely stiff and is capable of some degree of deformation when exerting a force. By fixing all degrees of freedom, an assumption is made that the hand is perfectly rigid, which leads to inaccurate results at the edges of the constraint.

22.3 FEA Evaluation

One method to account for the deformability of the hand is to use a spring element in the model. However, this is a very complex and time-consuming technique. The spring element will represent the stiffness of a hand and will deform slightly when a force is applied. By including a spring element, the behaviour of the hand can be better captured, and more accurate results can be obtained (Yan, 2012). This method should also account for the deformability of the hand and will produce more accurate results as the handle will deform closely to what would be observed in reality.

An example of this method being successfully used was during a study conducted by researchers at the University of California, Los Angeles (UCLA), where they developed a finite element model of the human hand and wrist to simulate the forces and deformations experienced during a lifting task. In their model, they included spring elements to represent the stiffness of the hand and wrist, allowing for more realistic deformations and better accuracy in the results (Yan, 2012).

Figure 66 is an image of the model created in the referenced document.



Figure 66 Model of Hand produced by the University of California (Yan, 2012)

The rope could also be implemented into the model, with force being applied to the rope itself, better representing the loads that would be observed during physical testing.

23.0 Methodology - Physical Experiment to compare with FE Model

23.1 Set-Up / Method

A physical test was performed on the single provided 3D printed prototype at EnerSys Newport to compare with the FEA results.

The prototype sample was set up in a tensile machine, as shown in Figure 67, with two pieces of wood used to ensure that the angle of the rope between the horizontal and vertical vectors is 90° (to replicate how it assembled into a battery). The piece of wood under the handle is a similar size to a hand / the FE model constraint shown in Figure 59. The clamps were tightened onto the pieces of wood to ensure that the handle and rope moved freely.

The speed of the machine was set to 50mm/min to simulate a hand slowly lifting a battery.

The grips then pull apart the pieces of wood until a failure occurs.



Figure 67 Prototype Handle Physical Test Set-up

24.0 Results - Physical Experiment to compare with FE Model

The sample withstood a load of 2529N which is approximately 25% greater than a factor of safety of 3. The failure mode was at the pip of the rope, as shown in Figure 68. This result is unexpected as the FEA results predicted that the sample would fail at a much lower load value and that the failure would occur at the thin section.

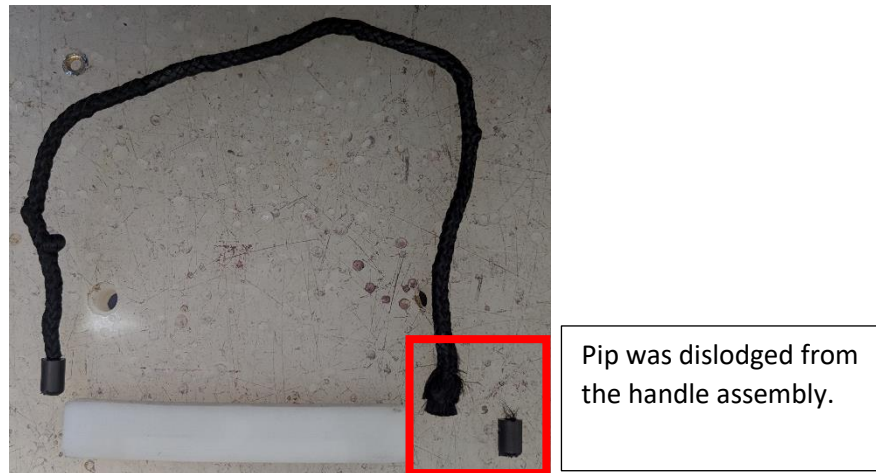


Figure 68 Prototype Sample Failure Mode Following Physical Test

25.0 Analysis - Comparison of results between FEA model and physical experiment

Although the sample size for the physical experiment is inadequate, it is vital to consider the contributing factors for the difference in results. The simulation predicted that the prototype model would not withstand a factor of safety of 3 and fail at the thin section. Whereas the physical experiment resulted in the model withstanding a factor of safety of 3 and failed at the rope pip.

25.1 Reasons for differences in results

Single point constraints - the constraints set for the hand that does not allow the part to move in 6 degrees of freedom heavily impacts the stress applied to the part at the edges of the constraint. The constraint does not allow the part to flex at the centre of the handle, which was observed during the physical test. This bending of the part will relieve stress from the thin section of the handle (section 2).

Loading assumption - the worst case set for the loading may be far from reality. Some loading may have been relieved from the vertical direction in favour of the horizontal direction.

25.2 Suggested steps forward

Based on the physical test results, the next step would be to perform a physical test to an acceptable sample size. Thirty prototype samples should be tested, and a capability study must be performed to ensure minimal variation in results. However, the material used for the prototype sample should be selected to closely match the tensile strength of the production material, as the current prototype material is 20% stronger in terms of tensile strength.

Based on whether the results are acceptable, some design changes can be made to improve the structural integrity of the prototype. Suggested improvements can be found in sections 28.1-28.3. A single cavity tool will be purchased if the LER prototype design is acceptable. Production samples will be produced and put through the EnerSys' PPAP process, which involves measuring all the critical dimensions of the samples, performing the relevant physical tests and performing a cosmetic inspection and, based on results determining whether they are fit for purpose (whether they meet our original requirements).

Buying handles from LER would be the preferable long-term solution as they are located in the same country as the EnerSys France plant, which currently produces the batteries for Daimler (which used to be produced in America). This will reduce supply chain costs.

EnerSys have also been informed by Rope and Plastics (current supplier) that two alternative rope suppliers show promising results. Currently, no data has been received.

26.0 Discussion

Unfortunately, this project was delayed throughout most of 2023 due to the prioritisation of higher-importance projects. As of May 2023, the current supplier (Rope and Plastics) has found two alternative rope suppliers and is currently assessing the strength of these ropes to the test methods defined in this report. They have claimed to have seen promising results.

There has yet to be further progress with Accuma's (alternative supplier) alternative design; however, after the analysis performed on the prototype design from LER, EnerSys Newport will soon receive 30 samples to perform physical testing to determine how much load this design can withstand accurately.

27.0 Conclusions

The project has met most of its objectives and is on track to completion. A baseline standard has been verified for the currently supplied samples. EnerSys has implemented a successful quality control procedure (short-term solution) and determined the root cause of the issue at hand: a change in the rope used for the handle. The currently supplied handles are acceptable under a concession, and three potential long-term solutions are being progressed. The current goal is to determine whether the prototype handle design from LER is acceptable and whether the current handle supplier's (Rope and Plastics) two alternative rope suppliers are acceptable.

28.0 Further Works

28.1 Potential improvements to LER prototype design

Based on the outcome of testing 30 prototype samples to the method defined in section 23.0, if the results of further testing are close to what was seen in section 22.0 (FEA results), then some improvements can be made to the design of the prototype to improve the structural integrity of the weakest point (thin section).

28.2 Altering the thin section to be flush with the top surface of the handle

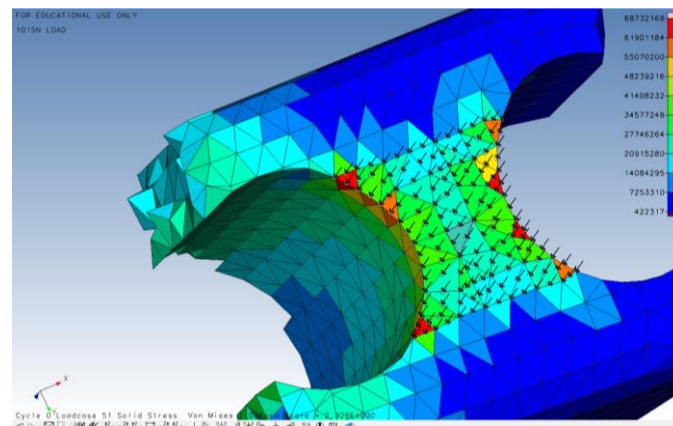


Figure 69 Thin section Modification to be flush with the top surface

The modification shown in Figure 69 halved the stresses applied to the thin section, which is a significant improvement to the initial design.

28.3 Increasing the thickness of the thin section

5mm Thickness

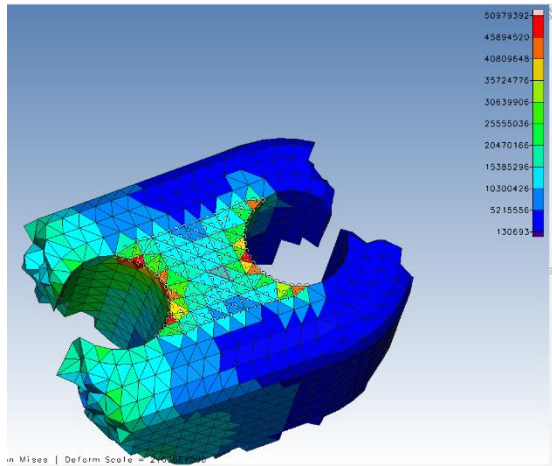


Figure 70 Figure 62 Modification + Increasing thickness of section to 5mm

8.5mm Thickness

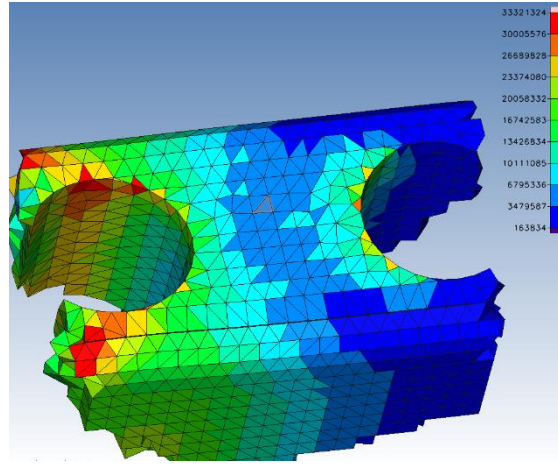


Figure 71 Figure 62 Modification + Increasing thickness of section to 8.5mm

Increasing the thickness of the section shown in Figures 70 and 71 is another alternative design change that also reduces the stresses exhibited in this area.

These alterations can be considered if results from additional testing are significantly different from that seen in section 24.0.

28.4 Alternative Rope Suppliers for the Current Handle Supplier

EnerSys Newport will perform a PPAP approval for the two new rope suppliers from which the current handle supplier (Rope and Plastics) have sourced.

28.5 Summary of Next Steps

28.5.1 Short-Term

Proceed with the approval of the LER (alternative supplier) prototype design shown in section 21.7 and the two potential rope suppliers for Rope and Plastics (current supplier).

Determine whether the current short-term control method can be improved to reduce the screening process costs shown in section 17.0.

Reinform suppliers that as per EnerSys stand procedure, any supply or product changes must be communicated to and pre-approved by EnerSys before implementation. Approval generally involves a PPAP approval and pre-production run.

28.5.2 Mid-Term

After initial approvals of potential long-term solutions, perform a PPAP inspection on production samples from Rope and Plastics; production can commence immediately provided they pass. For LER, a single cavity tool will need to be purchased, and a PPAP inspection will need to be performed on five samples. See section 25.2 for information on what a PPAP inspection entails.

Ensure that at least two manufacturers can supply EnerSys with suitable handles to ensure that a supply issue in the future will have minimal impact on production.

28.5.3 Long-Term and Project Importance

This project is a clear reminder of the importance of establishing multiple supply chains across product lines. The disadvantages of using a single source of supply become apparent such as the vulnerability of supply, the high risk of supplies being interrupted and the great dependency EnerSys had on a single supplier to ensure that production can still proceed (nibusinessinfo, 2020).

Having multiple sources of supply will ensure that EnerSys has less reliance on a single supplier and provides a safety net in case any difficulties arise. It will improve the flexibility of production and will ensure that suitable product is supplied whilst working on any issues with a specific supplier, heavily reducing the strain on product supply and EnerSys employees (nibusinessinfo, 2020).

The long-term priority will be to ensure that every product that is produced across the site has multiple sources of supply that can be used so that if a similar issue arises in the future, then EnerSys can buy products from an alternative supplier immediately and work on resolving the issue with the current supplier.

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Appendix A - Raw Data

N7500 ROPE HANDLE TEST

PART NUMBER HAN0029

DOC LEVEL 3

Requirement: The Locking Mechanism must withstand a minimum load of **800 N** over 5 cycles without any damage / displacement of the joint or fractures of the Rope Stands

TEST B					
R (N)					
Samples	New			Current	
	F (N)	Result		F (N)	Result
1	798	OK (750N)		1040	OK
2	729	Failed Cycle 5 (750N)		987	OK
3	939	OK (700N)		960	OK
4	908	OK (700N)		994	OK
5	709	OK (700N)		938	OK
6	640	Failed Cycle 5 (700N)		987	OK
7	889	OK (650N)		1030	OK
8	732	OK (650N)		1010	OK
9	813	OK (650N)		1040	OK
10	929	OK (650N)		1030	OK
11	645	Failed Cycle 3 (650N)		1040	OK
12	718	OK (600N)		1040	OK
13	786	OK (600N)		1030	OK
14	771	OK (600N)		982	OK
15	865	OK (600N)		938	OK
16	909	OK (600N)		903	OK
17	965	OK (600N)		1010	OK
18	741	OK (600N)		1010	OK
19	889	OK (600N)		995	OK
20	913	OK (600N)		1020	OK
21	769	OK (600N)		1050	OK
22	757	OK (600N)		1000	OK
23	797	OK (600N)		1000	OK
24	638	OK (600N)		878	OK
25	811	OK (600N)		956	OK
26	841	OK (600N)		1020	OK
27	767	OK (600N)		982	OK
28	829	OK (600N)		1050	OK
29	598	Failed Cycle 6 (600N)		1090	OK
30	867	OK (600N)		1000	OK
Moyenne	799	/		1000	/
Min	598	/		878	/
Max	965	/		1090	/
Ecart type	98	/		45	/

Difference %

-20,2

-31,9

-11,5

Remark:

F (N) is the final result of max load until damaged = stop of the tensile machine test

Figure 72 Raw data for Testing performed at EnerSys France comparing the currently supplied handle (new) and previously supplied handle (current) ignore incorrect labelling

Appendix A - Raw Data

Supplier Test Results following New Test Method for Locking Mechanism Strength 30 Samples Tested
621
739
776
647
666
950
900
800
826
754
702
679
757
895
909
882
912
789
878
757
829
798
864
647
787
816
843
827
764
785

Table 9 Rope and Plastics locking mechanism test results post-test method alignment

Appendix A - Raw Data

Locking Mechanism Test Results after Quality Control Procedure implementation (EnerSys France) 30 Samples Tested
746
849
759
834
795
962
784
826
868
874
792
856
912
864
780
879
912
813
888
858
916
847
832
798
879
789
914
834
882
829

Table 10 EnerSys France locking mechanism test results post-test method alignment

Appendix A - Raw Data

Horizontal Load Derivation through Physical Testing	
Applied Vertical Load	Resultant Horizontal Load
400	247
400	227
400	263
400	255
400	251
400	260
400	241
400	258
400	246
400	243
400	231
400	261
400	243
400	256
400	237
400	235
400	247
400	244
400	257
400	240
400	242
400	260
400	232
400	245
400	239
400	241
400	248
400	259
400	245
Average = 246.66	

Table 11 Horizontal Load Derivation - Testing Results