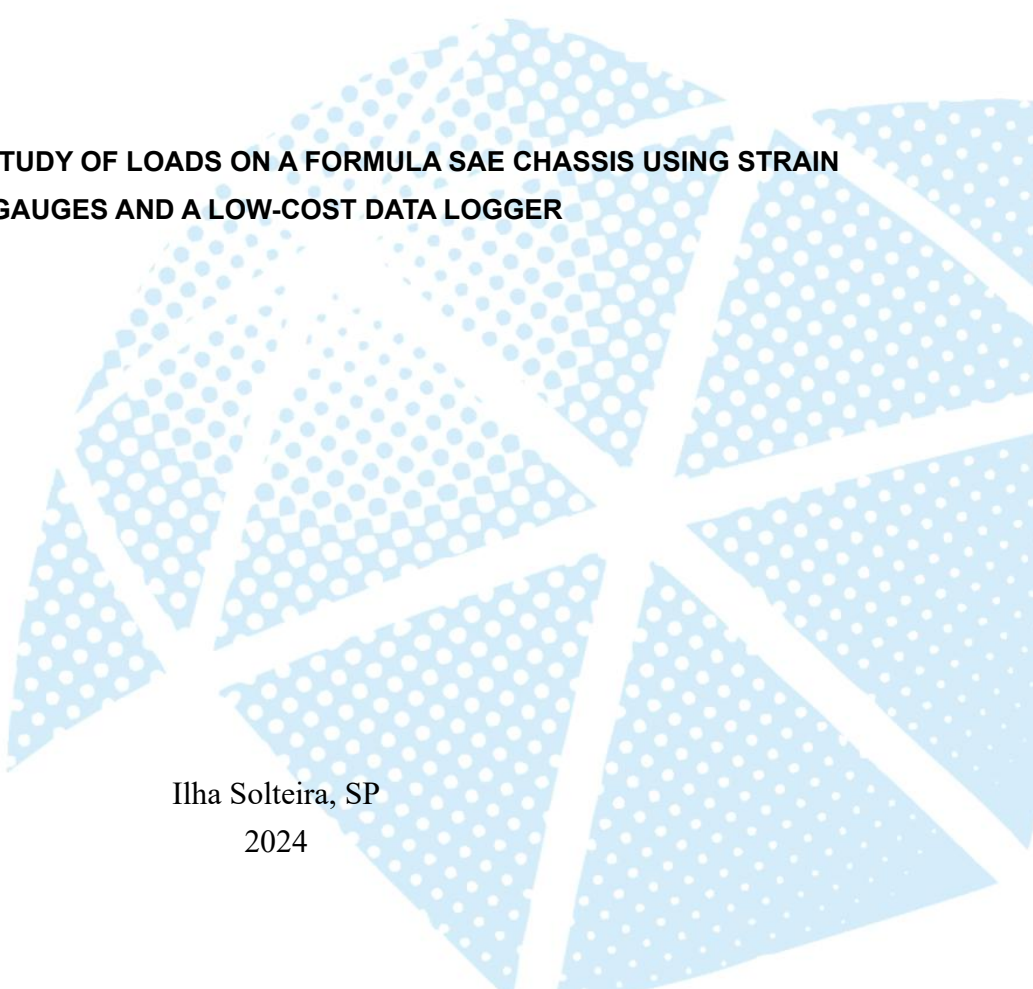


**SÃO PAULO STATE UNIVERSITY
ILHA SOLTEIRA SCHOOL OF ENGINEERING**

MARIO FINATO CESTARI

**AN EXPERIMENTAL STUDY OF LOADS ON A FORMULA SAE CHASSIS USING STRAIN
GAUGES AND A LOW-COST DATA LOGGER**

Ilha Solteira, SP
2024



Mario Finato Cestari

**AN EXPERIMENTAL STUDY OF LOADS ON A FORMULA SAE CHASSIS
USING STRAIN GAUGES AND A LOW-COST DATA LOGGER**

Undergraduate Thesis presented to the Ilha
Solteira School of Engineering – UNESP as part
of the requirements for obtaining the degree of
Mechanical Engineer

Márcio Antonio Bazani
Advisor

Ilha Solteira, SP

2024

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ATA DE DEFESA DO TRABALHO DE GRADUAÇÃO

Aos 10 dias do mês de dezembro do ano de 2024, às 18h, videoconferência do Departamento de Engenharia Mecânica, da Faculdade de Ilha solteira, o discente Mario Finato Cestari, matriculado sob o nº 182054071, tendo como banca examinadora, o orientador Professor Doutor Márcio Antonio Bazani, apresentou o Trabalho de Graduação intitulado “An Experimental Study of Loads on a Formula SAE Chassis Using Strain Gauges and a Low-Cost Data Logger”, obtendo a nota final 10.

Por ser verdade, os membros da banca examinadora e o discente assinam em seguida.

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I hadn't considered writing a dedication for this thesis until I came across the following: "This thesis is dedicated to everyone who recognizes and values student competition projects. It is also dedicated to those who do not, so they may come to appreciate the importance and significance of these activities" (Pereira, 2017).

I also dedicate this thesis to everyone who, day by day, works in an effort to contribute to the evolution of society.

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To the Fenix Racing team, which was a place where I was able to learn a lot about many things, even about myself, helping me grow and providing truly memorable moments.

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To my friends, who have always helped me with technical and personal matters, and especially with the entertainment during our social meetings, always making everything much lighter and funnier.

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“We join the team for the car, but we stay for the people.”

— Paulo Vinicius Maia Lucas

ABSTRACT

In a complete engineering project, the validation process is of great importance, as it is the phase where you can analyze the results of all the others. In a Formula SAE team, where the main objective is learning through hands-on experience, this value should be even stronger. FSAE Brazil currently emphasizes this, requiring it during the design presentation. Unfortunately, the Fênix Racing Team has faced many troubles with the validation process, mainly due to a lack of materials, reliance on third parties, and unpredictability of the schedule. This work aims to address this issue by developing a low-cost data logger using an Arduino board, a data logger shield, an HX711 module, and a complete Wheatstone bridge of strain gauges. The initial idea was to test this system on the car chassis, but that was not possible. The system was tested on a cantilever beam, calibrated with a series of static loads using known weights, and tested with an impact and a pendulum system, both simulating dynamic loads. The system performed well in the second case, with an error of less than one percent. The results are very promising and could serve as a starting point for a more effective validation phase within the team.

keywords: validation. data logger. strain gauge. low-cost. Formula SAE.

RESUMO

O processo de validação desempenha grande importância na competência de um projeto de engenharia, pois é a fase em os resultados de todas as outras etapas são analisados. Em uma equipe de Formula SAE, onde o principal objetivo é o aprendizado através de experiências práticas, esse princípio deve receber ainda mais destaque. Atualmente a competição Formula SAE Brasil se alinha com esse ideal, exigindo a presença da etapa de validação durante a apresentação da prova de design. Infelizmente a equipe Fênix Racing tem enfrentado muitas dificuldades no processo de validação, principalmente devido à falta de equipamentos, dependência de terceiros e imprevisibilidade do cronograma. Este trabalho tem como objetivo abordar esse problema desenvolvendo um sistema de aquisição de dados de baixo custo, utilizando uma placa Arduino, uma shield de data logger, um módulo HX711 e uma ponte completa de Wheatstone de extensômetros. A ideia inicial era testar este sistema no chassi do carro, mas isso não foi possível. O sistema foi testado em uma viga em balanço, calibrado com uma série de cargas estáticas utilizando pesos conhecidos, e testado com um impacto e um sistema de pêndulo, ambos simulando cargas dinâmicas. O sistema apresentou bom desempenho no segundo caso, com erro inferior a um por cento. Os resultados são muito promissores e podem servir como ponto de partida para uma fase de validação mais eficaz dentro da equipe.

Palavras-chave: validação. data logger. extensômetro. baixo custo. Formula SAE.

LIST OF FIGURES

Figure 1 – Formula SAE competition 2022	2
Figure 2 – Team areas diagram	3
Figure 3 – Truck trailer chassis	4
Figure 4 – Simply supported beam	4
Figure 5 – Suspension system and it loads	5
Figure 6 – Suspension loads indicated on the car	6
Figure 7 – Conventional strain gauge data logger systems	7
Figure 8 – Low-cost data logger	7
Figure 9 – Side impact members	9
Figure 10 – Simplified model	10
Figure 11 – Chassis on the torsional stiffness mount	10
Figure 12 – Straing gauge compared to a pen tip	11
Figure 13 – Fixture and circuit of the strain gauges	11
Figure 14 – Strain gauges fixed on the tube	12
Figure 15 – Data logger circuit	13
Figure 16 – Skidpad course	14
Figure 17 – Final setup	14
Figure 18 – Setup for impact procedure	15
Figure 19 – Pendulum setup	18
Figure 20 – Raw data registred	18
Figure 21 – Raw experience data	20
Figure 22 – Raw experience data without outliers	21
Figure 23 – Calibration curve	22
Figure 24 – Impact dinamic load testing	22
Figure 25 – First impact	23
Figure 26 – Pendulum dinamic load testing	24
Figure 27 – Pendulum dinamic load testing without outliers	25
Figure 28 – 16th pendulum release	25

LIST OF TABLES

Table 1 – Strain gauges specifications	12
Table 2 – Known masses and calculated weights	16
Table 3 – Values used on calculations	16
Table 4 – Collected data	20
Table 5 – Calibration curve values	21
Table 6 – Impact results	23
Table 7 – Pendulum results	26
Table 8 – Final results	26
Table 9 – Data logger systems velocity and price	26

LIST OF ABBREVIATIONS AND ACRONYMS

ADC	Analogic Digital Converter
AISI	American Iron and Steel Institute
BSIM	Bottom Side Impact Member
DSIM	Diagonal Side Impact Member
<i>ECPA</i>	<i>Esporte Clube Piracicabano de Automobilismo</i> - Motor Sports Club of Piracicaba
FAT	File Allocation Table
FSAE	Formula Society of Automotive Engineering
INA	Instrumentation Amplifier
LCDL	Low-Cost Data Logger
RAM	Random Access Memory
SAE	Society of Automotive Engineering
<i>SAE Brasil</i>	Brazilian branch of the Society of Automotive Engineering
SES	Structural Equivalency Spreadsheet
SG	Strain Gauge
SIM	Side Impact Members
SPS	Samples per Second
USIM	Upper Side Impact Membe

LIST OF SYMBOLS

E	Elasticity Eodulus
F	Force
g	Gravity Aceleration
h	Height
I	Area Moment of Inertia
k	Stiffness
K	Kinect Energy
ℓ	Beam Length
L	Pendulum Length
$load_{max}$	Maximum Expected Vertical Load
m	Mass
M_b	Active Bending Moment
T_{max}	Maximum Expected Pendulum Tension
U	Energy
v	Velocity
W	Weight
V_{EX}	Exitation Voltage (Wheatstone bridge input)
V_{CH}	Measured Voltage (Wheatstone bridge output)
Δy	Vertical Displacement
θ_0	Pendulum Release Angle

CONTENTS

1	INTRODUCTION	1
1.1	Formula SAE	1
1.2	Chassis	3
1.3	Objective	6
2	METHODOLOGY	8
2.1	Literature Review	8
2.2	Phisic Model	9
2.2.1	Strain Gauge	10
2.2.2	Data Logger	12
2.3	Final Setup and Experimental Procedure	14
2.4	Data Collection and Analyses	18
3	RESULTS	20
4	CONCLUSION	27
4.1	Recommendations for Future Research	27
	References	28
	APPENDIX A – ARDUINO CODE	30

1 INTRODUCTION

Validation is one of the most important stages in an engineering project, primarily because it confirms the effectiveness and reliability of earlier phases such as design and manufacturing. An engineering project without a validation phase can be considered unreliable and even incomplete. This reasoning parallels the scientific method, where experimentally observed results must align with those predicted by theory for a hypothesis to be deemed validated.

Factors such as budget constraints, time limitations, and lack of experience often make the validation phase particularly challenging for many Formula SAE teams. Therefore, continuously seeking ways to address these issues should be a priority for every member of a Formula SAE team, such as implementing efficient project management strategies or leveraging mentorship from experienced teams.

1.1 Formula SAE

Formula SAE is a motorsport category aimed at the engineering educational institutions, designed to provide students with an opportunity to apply classroom knowledge through the comprehensive development of a single-seat prototype vehicle (Brasil, n.d.).

The category originated in the United States at the University of Texas in the early 1980s. In the initial competitions, major automotive brands such as Ford and General Motors were deeply involved with the event, even hosting some editions. These and other companies saw the category as an excellent source for recruiting engineers with education tailored to their needs, as well as for exploring new technologies that could be applied to their products (Case; Matthews, 2010).

The competition, organized by the Brazilian branch of the Society of Automotive Engineering (SAE *Brasil*), takes place annually at the Motor Sports Club of Piracicaba (ECPA), bringing together approximately sixty teams with combustion and electric cars and over twelve hundred engineering students. During the event, teams undergo three main types of inspections: safety, presentation, and dynamic events.

Safety inspections are mandatory, aiming to ensure the physical integrity of all event participants, as well as good engineering practices. The submission of documentation prior to the competition can be considered part of this process, especially due to the requirement of the Structural Equivalency Spreadsheet (SES). Upon arrival at the event, both equipment and the vehicle must undergo technical inspection. Subsequently, the car needs to pass a sequence of three tests: the Tilt-Table, Noise, and Brake, before finally being cleared for the dynamic events.

Presentation events are qualifying rounds, evaluating the overall project through various

topics such as cost and manufacturability, feasibility of serial production, project management, validation, team evolution, and component finish quality, among others.

Dynamic events are also qualifying and represent the pinnacle of the Formula SAE experience for most competitors. Cars are driven by team members aiming to achieve the maximum possible points on different tracks: Acceleration, where the car must cover 75 meters from a standstill in the shortest time possible; Skidpad, where the car completes four laps in a figure-eight course to test cornering capability; Autocross, an approximately 800 meter course that challenges car nimbleness and driver skill, heavily influenced by drivability; and Endurance, the longest and most challenging dynamic event at approximately 22 km, which primarily tests car reliability but requires a complete performance from the project (SAE, 2023).

In over fifteen years of history, the Fênix Racing Team has never completed an Enduro race during a competition.

An interesting description of how participating in such a team contributes to the formation of an engineer was presented by Alan Gruner in his article about Formula SAE team management: “In classes we are generally given clearly defined problems that include all the data needed to solve them and that have narrowly defined ranges of “right” answers. On this project you will be continually presented with problems that are ambiguous. There will be many solutions that will work and no “right” answers. You will not have all the information you need. This is where you start learning real engineering and management skills. If you don’t know something, you must go learn it. The real world is ambiguous; start getting comfortable with it. Engineering is not a science. It is the art of finding solutions and making good choices. Science only provides the paints and brushes you will use” (Gruner, n.d.) (Pereira, 2017).

Figure 1. Formula SAE competition 2022



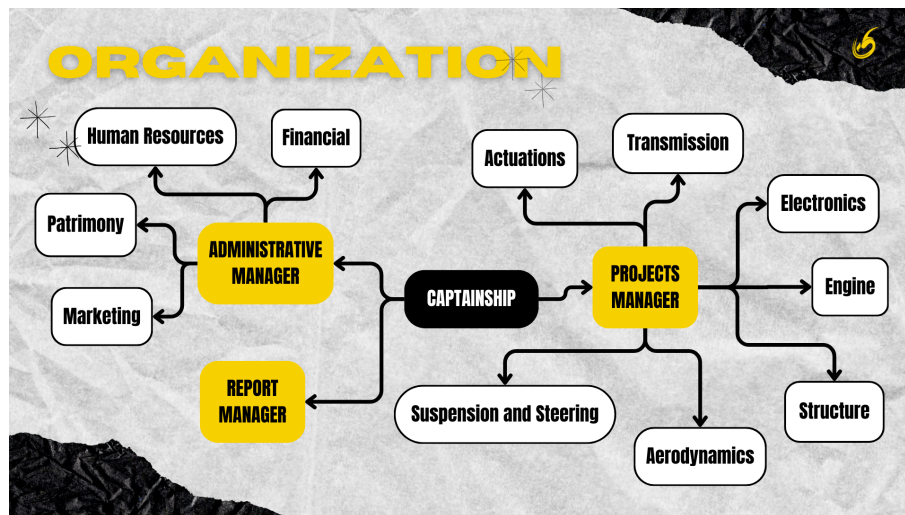
Source: Fênix (2024)

1.2 Chassis

The chassis is one of the most critical components of a vehicle, consisting essentially of a main structure to which all other components are mounted. Its role in the car can be compared to that of the skeleton in the human body.

The team is organized into areas responsible for specific systems, subsystems, and components of the prototype, allowing for better division and management of the responsibilities inherent in a complex project like vehicle design. This structure is illustrated in Figure 2. For instance, the chassis is the primary component overseen by the Structure area, along with elements such as the floors, firewall, seat, and impact attenuator.

Figure 2. Team areas diagram



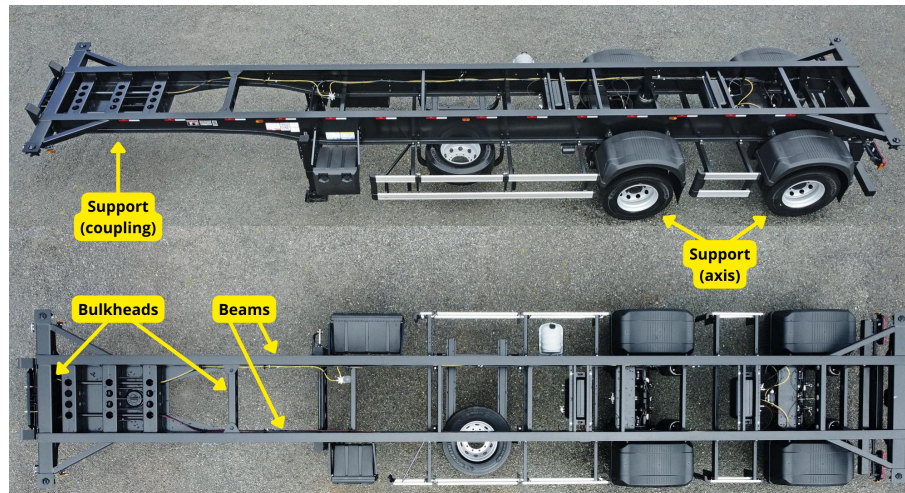
Source: Fênix (2024)

Because of the integrative role the chassis plays, it must meet various requirements across different areas. These specifications can be geometric, such as the dimensions of the rear section to accommodate the engine, or they may involve achieving the necessary mechanical resistance to endure specific load demands.

The types of loads applied to the chassis play a crucial role in determining its construction. A clear example is the chassis of a truck trailer, illustrated in Figure 3. Since it is designed to transport heavy loads, a truck chassis must primarily withstand high bending stresses, much like a classic simply supported beam, as depicted in Figure 4.

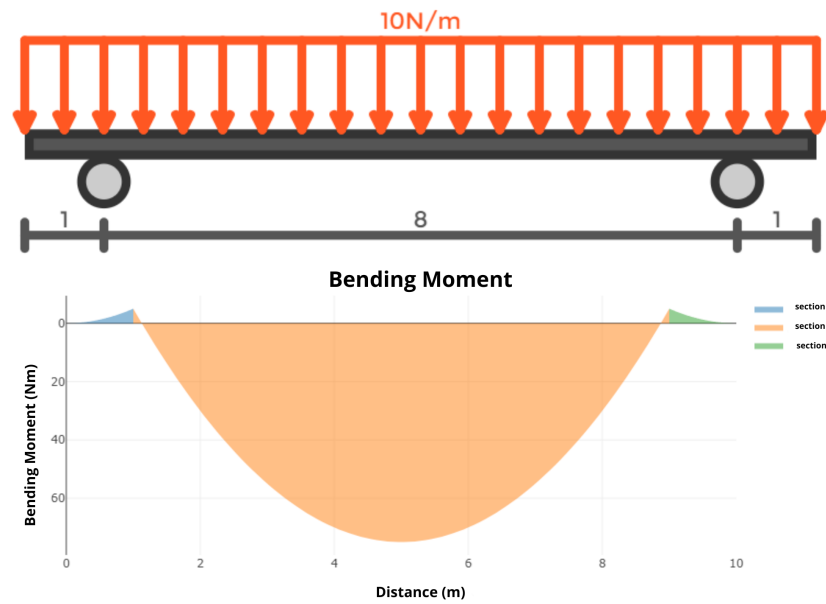
This leads to the truck chassis having a simple yet robust geometry, consisting primarily of two parallel beams connected by cross sections (bulkheads). Moreover, since nearly the entire chassis lies within a single plane, the ratio of torsional to flexural rigidity is significantly lower than that of any chassis occupying multiple planes in space. Consequently, it is reasonable to conclude that a racing car chassis will differ markedly from a truck chassis. Additionally, factors such as cost and ease of manufacturing play a significant role in the chassis design process.

Figure 3. Truck trailer chassis



Source: adapted from Facchini (n.d.)

Figure 4. Simply supported beam



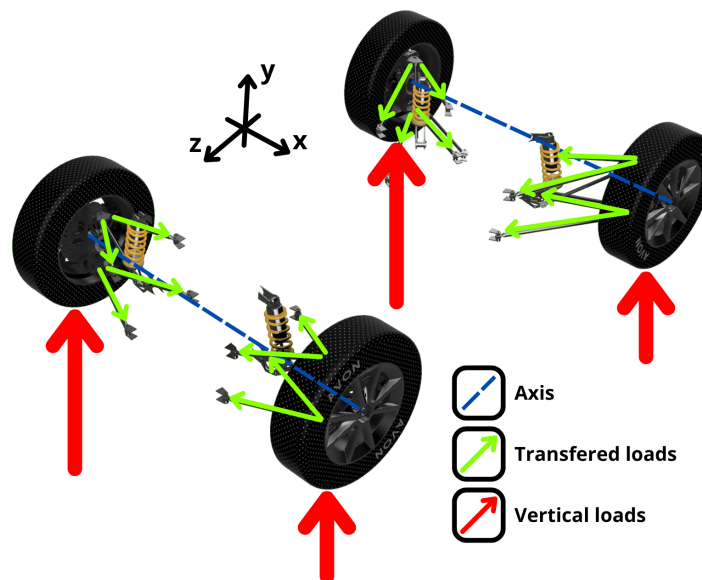
Source: author

In order to better understand the main forces acting on the chassis, the following abstraction can be made: the car is essentially a body moving through space, with this "space" defined by the track, and the only contact area between the car and the track is the tire contact patch. Additionally, we can consider aerodynamic forces resulting from interaction with the air; however, this will not be the focus of this study, primarily due to the low speeds at which the vehicle operates. All these interaction forces between the car and the track occurring at the tire surface are transferred to the chassis through the suspension components.

Continuing with this abstraction, this body is set in motion by the torque generated by the engine and transmitted to the tire; therefore, the support points of the engine and transmission components also deserve attention due to the reaction forces, which ultimately act on the tire. Following this line of thought, the most important demands placed on the Structure team stem from the suspension system.

From a drivability standpoint, a stiffer chassis is preferable, as its effectiveness depends solely on the quality of the suspension design. The loads from the suspension act on the chassis in the transverse planes relative to the axes, making the stiffness between these two planes of great significance. The Figures 5 and 6 help visualize all these loads and directions; however, the arrows in the images only illustrate the directions of the forces, which constantly vary in intensity and direction when the car is in motion. The "transverse planes relative to the axes" refer essentially to the yz planes crossed by the dashed blue lines.

Figure 5. Suspension system and it loads

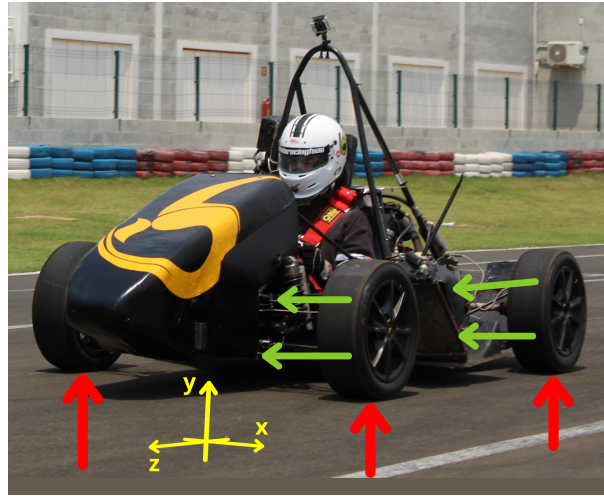


Source: adapted from Fênix (2024)

The vertical loads are the most significant forces transmitted through the suspension to the chassis. If the sum of these loads across the two diagonals results in different values, the chassis experiences torsional stress. For cornering, the suspension is typically designed to create mechanisms, such as the anti-roll bar, that convert vertical forces into desirable lateral forces, thereby enhancing vehicle control to maintain the racing line (Dixon, 1996).

This discussion naturally leads to the question: what is the target stiffness for the chassis? While greater stiffness is advantageous, achieving it often requires the addition of elements to the chassis, which consequently increases its mass. This added mass can negatively impact the design due to increased inertia. Therefore, the challenge lies in finding a balance between stiffness and mass.

Figure 6. Suspension loads indicated on the car



Source: adapted from Fênix (2024)

The literature is somewhat confusing in this regard; Riley and George (2002) aim to identify this balance point by analyzing a function that relates vehicle stiffness to chassis stiffness. As a small increase in vehicle stiffness requires a significant increase in chassis stiffness, this increment can be considered disadvantageous. Therefore, analyzing the rate of variation is quite pertinent in this case.

Kerkhoven (2008) proposes an analysis that focuses solely on roll stiffness, as this factor also significantly influences vehicle stiffness. He states that a coherent target value lies between 3 and 6 times the roll stiffness. For example, the Formula Student vehicle he discusses has a roll stiffness of about $870 \text{ Nm}/^\circ$, so the target value for the chassis's torsional stiffness would be between 2610 and $5220 \text{ Nm}/^\circ$.

Thus, the chassis is designed to achieve a specific torsional stiffness and mechanical strength based on suspension parameters, as the attachment points for the suspension components also endure significant forces. The issue arises from the fact that the values provided by the suspension in our team have always been theoretical. Therefore, no static or dynamic tests have been conducted to validate these values.

1.3 Objective

This study aims to obtain the values of the forces acting on the chassis during a dynamic test of the car, verifying whether the theoretical values align with reality. This serves a validation function for the project. Since we do not yet have this data, any values obtained will represent a significant advancement, providing at least an estimate of the order of magnitude of these loads. Additionally, the desire to achieve better results in Frame design presentations motivates this study.

The team's very limited financial resources consistently pose a challenge; therefore, the "low-cost data logger" (LCDL) is a key component of this work. The university has some equipment that can be used as strain gauge data loggers, similar to those shown Figure 7. However, these devices present several problems: they are very expensive, costing thousands of dollars; they lack portability, preventing us from using them in a running car; and they do not belong to the team, making their use complicated.

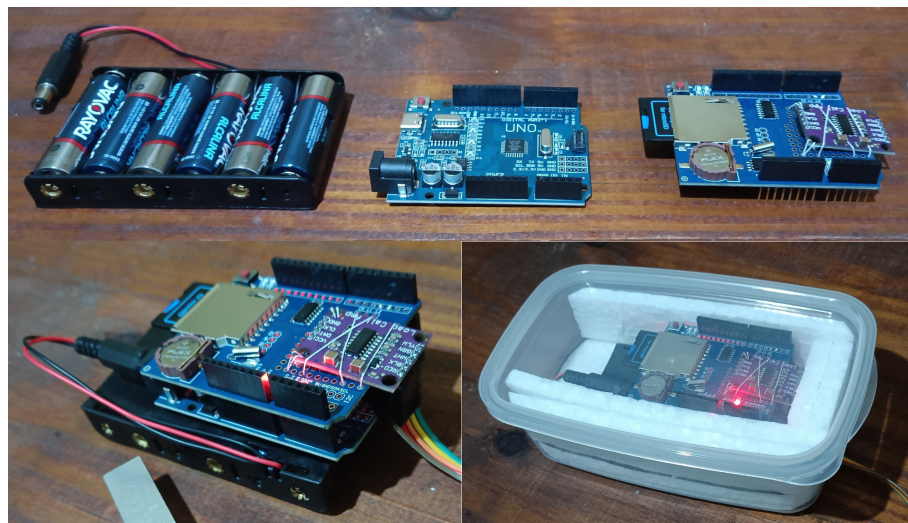
Figure 7. Conventional strain gauge data logger systems



Source: adapted from Andolfato, Camacho, and Brito (2004)

The idea of addressing all these specific needs is to use a prototyping microcontroller platform as a signal conditioner. The Arduino UNO R3, which features the ATmega328P microcontroller, costs about twelve dollars in Brazil and is very portable, fitting into a small plastic container. It saves collected data on a micro SD card, is powered by an external battery, and can be programmed from a laptop.

Figure 8. Low-cost data logger



Source: author

2 METHODOLOGY

2.1 Literature Review

Taking inspiration from previous team members' work, such as the development of a telemetry system for Formula SAE vehicles by Fernandes (2022) and a data logger for classic vehicle maintenance indicators by Murari (2023), along with various Arduino-based systems developed in the electronics and suspension areas, it became evident that creating a low-cost data acquisition system for chassis applications is entirely feasible.

In addition, similar systems relevant to this study's goals have been well-documented, like the one developed by Silva *et al.* (2019) using the ADS1230 integrated circuit, which, while more expensive than the HX711, performs similarly. Another example is found in Hemeda, Aboukarima, and Minyaw (2017), which uses the HX711 but operates at a lower sampling rate of around 20 SPS. Achieving a higher sampling rate is crucial here, as it enhances output reliability during dynamic loads—precisely what is being pursued in this study.

Initially, the plan was to calibrate the system during a torsional stiffness test, following the procedures outlined by Riley and George (2002). This involved applying a known torque to the chassis and measuring the resulting output to generate a calibration curve. The intention was then to gather real-time data with the car on track. However, as previously noted, unpredictable challenges arose as manufacturing concluded and testing for the competition began, preventing this direct testing method.

The alternative was to conduct tests in a closely related setup with minor adjustments. Strain gauges were affixed to a separate tube with specifications matching those of the upper side impact member. Based on the physical model, this tube was securely supported and subjected to known bending loads, which facilitated the calibration curve development. To simulate on-track data acquisition, a weight was dropped at the tube's end to create a dynamic bending load, with the aim of inferring this applied load. Later, a pendulum system was also employed for similar testing.

Due to these adjustments, Example 1.4 from Rao (2010) was widely referenced, along with fundamental concepts from Halliday, Resnick, and Walker (2012), which will be discussed in further detail in the methodology section.

The decisions about which materials and methods to use were driven by cost, availability of information, and the ability to meet the application's requirements. The system was going to be calibrated during a torsional stiffness test, and the loads to be measured came from the suspension. Therefore, the Skid Pad is an excellent track type to use as a dynamic test for data collection, as the highest suspension loads occur during this test, likely allowing us to collect

the peak values acting on the chassis.

2.2 Phisic Model

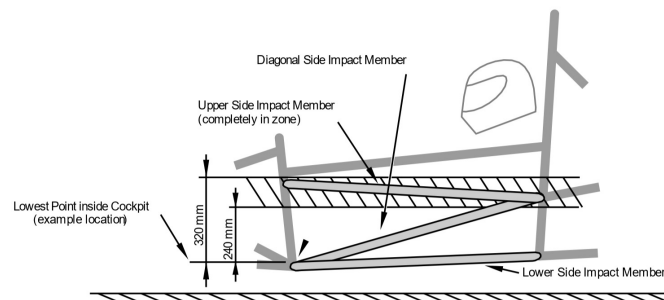
The use of strain gauges heavily depends on how they are fixed and connected. The best method for doing so is determined by the type of load the element is subjected to, such as compression, tension, shear, torsion, and bending. To determine the load type at the point where the strain gauges will be installed, we need to create a physical model that represents a simplification of the real chassis.

In this initial study, it was decided to fix the strain gauges to the central part of the upper side impact member. This tube is located between the rear and front axle fixture points and is an important member for transferring torsional loads. The plan is to use the torsional stiffness test to calibrate the strain gauges. Thus, this region emerged as a suitable starting point in the quest to better understand how loads act on the chassis.

Figure 9. Side impact members

F.6.4 Side Impact Structure

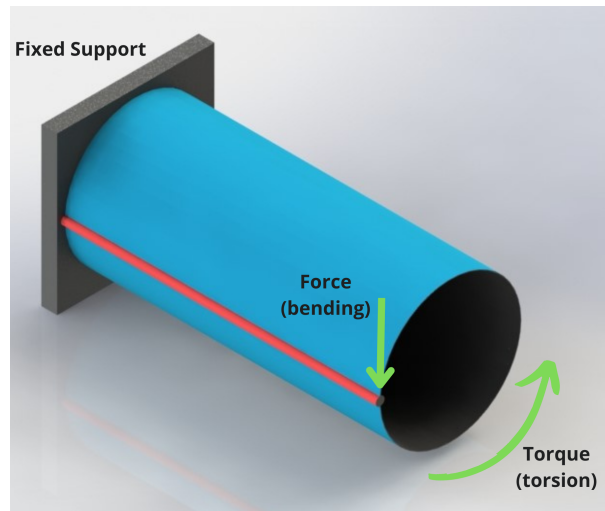
- F.6.4.1 Frame Members of the Side Impact Structure must be constructed of closed section tubing meeting **F.3.2.1.e** or **F.3.2.1.f**, as applicable
- F.6.4.2 With proper Triangulation, Side Impact Structure members may be fabricated from more than one piece of tubing.
- F.6.4.3 The Side Impact Structure must be comprised of three or more tubular members located on each side of the driver while seated in the normal driving position



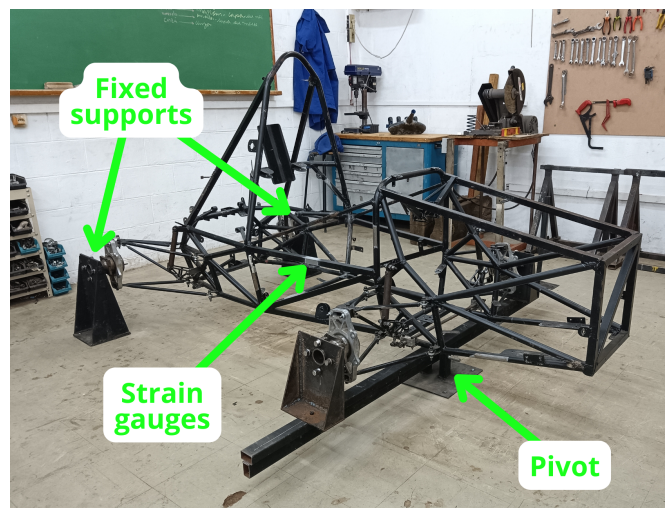
- F.6.4.4 The Upper Side Impact Member must:
 - a. Connect the Main Hoop and the Front Hoop.
 - b. Be entirely in a zone that is parallel to the ground between 240 mm and 320 mm above the lowest point of the top surface of the Lower Side Impact Member

Source: SAE (2023)

Following this line of thinking, the idealization treats the entire space frame as a cylindrical body, with the side impact members positioned on the outer surface of this cylinder. This allows us to deduce that when the chassis is subjected to torsional forces, as in a torsional stiffness test, the tube experiences a bending load, similar to a cantilever beam. This concept is illustrated in the image below, where the blue cylinder represents the chassis and the red element represents the upper side impact member.

Figure 10. Simplified model

Source: author

Figure 11. Chassis on the torsional stiffness mount

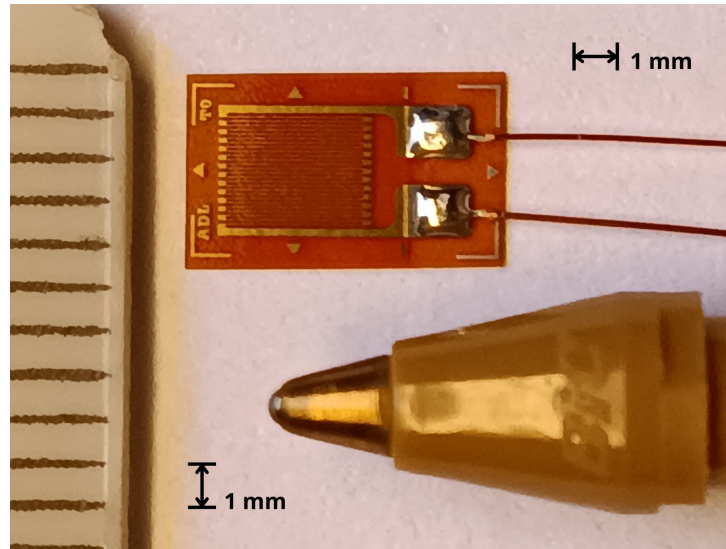
Source: author

2.2.1 Strain Gauge

It was decided to use strain gauges because they can measure the load applied to an element based on its strain, allowing for load measurement without interfering with the system. Additionally, since they function as transducers, acting as variable resistors, they enable the recording of values using a simple electronic system capable of capturing a high rate of samples per second (SPS), which can be easily stored during data collection and analyzed afterward.

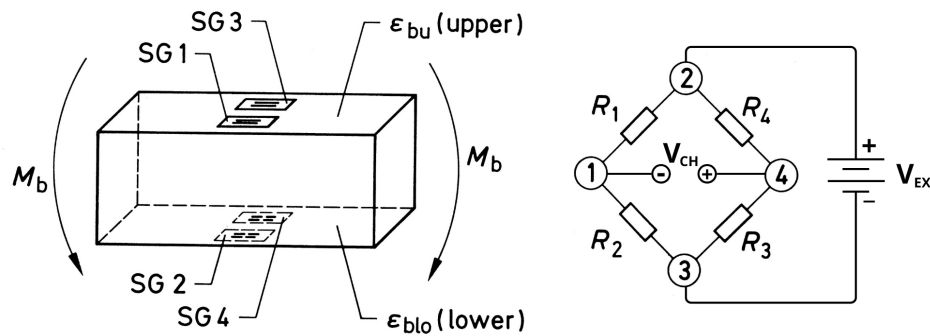
The element where the strain gauges will be installed will undergo a bending load. Consequently, based on Hoffmann (2012), the strain gauges should be positioned as shown in Figure 12, which also illustrates the circuit configuration. Drawing an analogy to a hydraulic system, this circuit functions like a flow control valve, in this case regulating the flow of electric current.

Figure 12. Straining gauge compared to a pen tip



Source: author

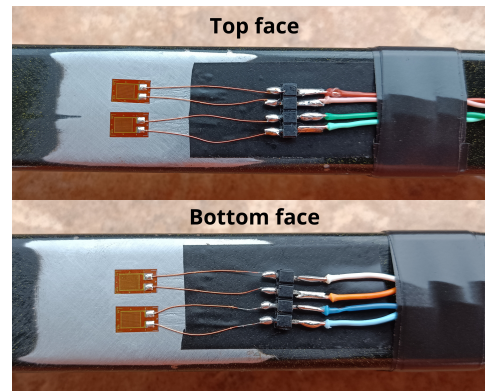
Figure 13. Fixture and circuit of the strain gauges



Source: adapted from Hoffmann (1989)

SG 1 and 3 will experience tension, increasing their resistance, while SG 2 and 4 will undergo compression, decreasing their resistance, or vice versa. The use of this configuration, where you essentially have two SGs performing the same function, helps increase the sensitivity of the system and also prevents potential issues caused by thermal expansion. For instance, if the tube expands, all four SGs will increase their resistance proportionally, without affecting the output value.

The strain gauges are used in a Wheatstone bridge circuit, as shown in Figure 13, where an excitation voltage (V_{EX}) is applied between points 2 and 3, and the measured voltage (V_{CH}) is taken between points 1 and 4. The decrease in the resistance of SG 2 and 4, or the increase in the resistance of SG 1 and 3, results in an increase in the measured voltage, indicating an increase in the active bending moment (M_b). If M_b is close to zero, all the SGs should have the same length and the same resistance, meaning V_{CH} should be near zero (Hoffmann, 1989).

Figure 14. Strain gauges fixed on the tube**Source:** author

The square tube was ground in an “X” pattern, and the strain gauges were bonded using low-viscosity ethyl cyanoacrylate (standard instant adhesive) along with regular adhesive tape, which proved to work very well. The soldering process was challenging due to the lack of appropriate solder terminals. After being secured, a layer of school glue was applied to protect the strain gauges and the ground area from humidity.

Table 1. Strain gauges specifications

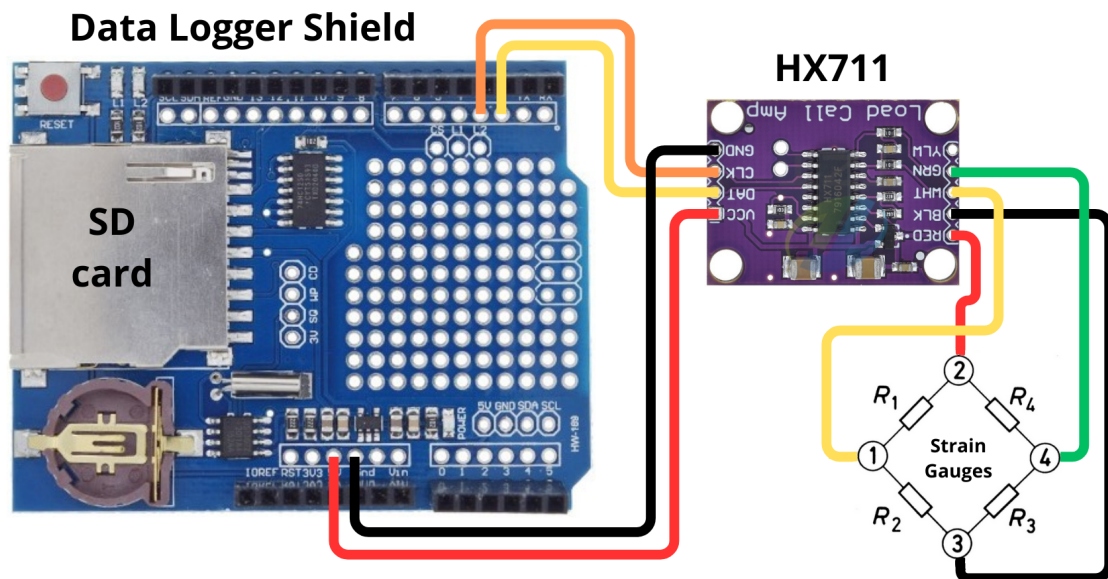
Item	Value	Unit
Type	BF350-3AA	-
Resistance	349.8 ± 0.1	Ω
Sensitivity coefficient (gauge factor)	2.00 - 2.20	-
Accuracy class	0.02	-
Strain limit	2000	microstrain
Monolithic size	7.1×4.1	mm
Brand	Tuozhanteng (TZZT)	-
Price	0.235	USD each

Source: author

2.2.2 Data Logger

The data logger is built using components such as the Arduino UNO R3, data logger shield, HX711 module, SD card, and a power supply. Some connections are explained in Figure 15. After that, the data logger shield is attached to the Arduino board, along with the power supply, as shown in the setup of Figure 8. This results in a fully independent system capable of communicating with the strain gauge full bridge and storing data on a micro SD card at 80 samples per second (SPS).

Figure 15. Data logger circuit



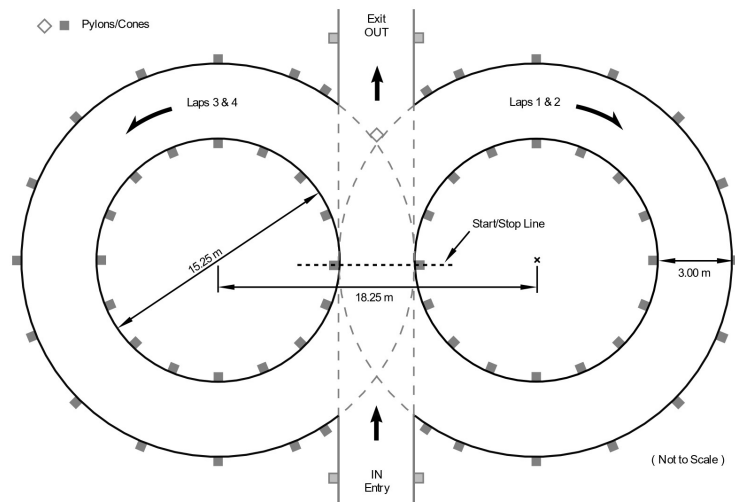
Source: author

The HX711 module is originally designed to be used with load cells, such as those found in kitchen scales, which utilize a full bridge of strain gauges, similar to the one used in this project. The module stabilizes V_{EX} , functioning as both an instrumentation amplifier (INA) and an analog-to-digital converter (ADC), amplifying and converting V_{CH} . It is important to note that to increase the sampling rate of the HX711 board, a connection on the bottom of the board labeled “RATE” must be cut.

The primary function of the Data Logger Shield is to interface all components with the Arduino board, including the SD card and the HX711 module, which are soldered to ensure a secure connection without requiring permanent modifications to the Arduino board. Using this setup, a maximum sampling rate of 80 SPS was achieved.

This rate should be sufficient, considering that Fênix Racing team’s best time at the skid pad event in the 2024 competition was 12.62 seconds. The distance covered on the track is approximately 114.7 meters, resulting in an average speed of about 9.09 meters per second. This means the distance between samples is around 11.36 centimeters.

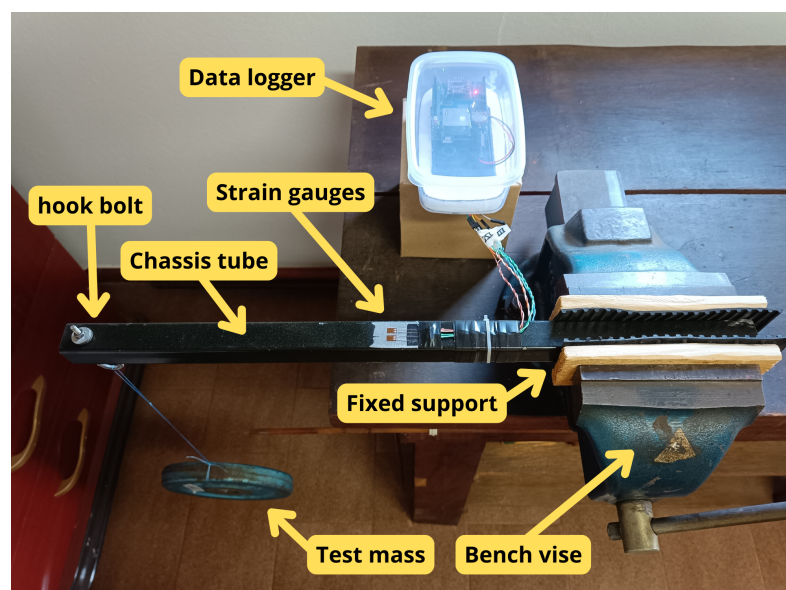
Therefore, a peak force will only go unrecorded if it occurs within a time interval shorter than this distance. Additionally, the car should cover about half of the total distance while experiencing the highest lateral acceleration, despite the track’s geometry.

Figure 16. Skidpad course

Source: SAE (2023)

2.3 Final Setup and Experimental Procedure

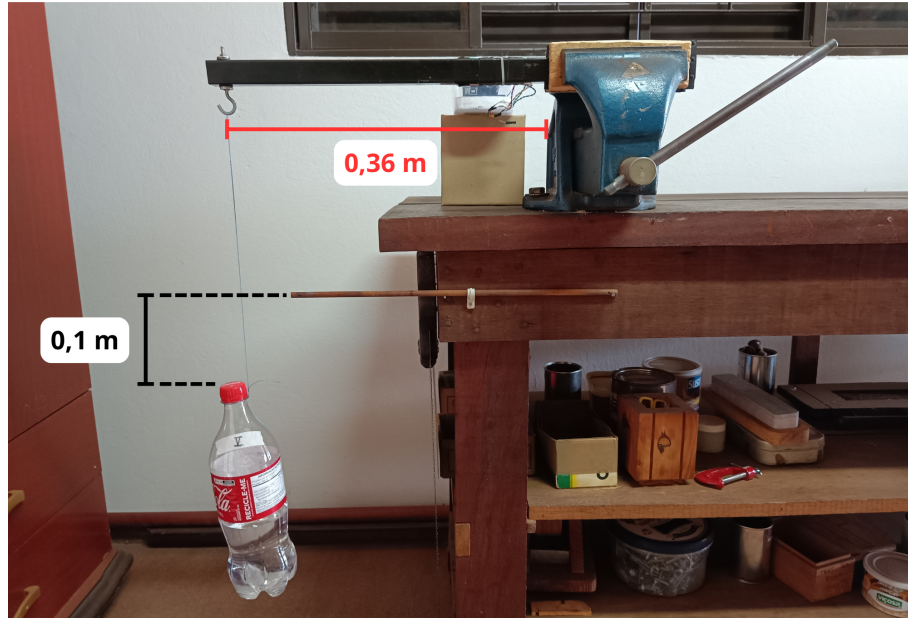
Due to some challenges in using the chassis as a test body for this work, an alternative test body was selected to proceed with the analysis: a square-section tube with the same specifications as the upper side impact member. This tube has a width of 1 inch, a wall thickness of 1.2 millimeters, and is made of AISI 1020 carbon steel. The tube was instrumented with strain gauges, and a hook bolt was attached to one side. Afterward, it was mounted in a bench vise as a fixed support.

Figure 17. Final setup

Source: author

The experiment uses static loads to create the calibration curve of the instrumented tube and variable loads to validate the system's capability. The static loads for the experiments were generated by the gravitational force acting on known masses. For the variable loads, these masses were set into motion, and the theoretical maximum values for the vertical component of the load were calculated using the concept of energy conservation.

Figure 18. Setup for impact procedure



Source: author

$$W = mg \quad (1)$$

All weight values from Table 2, excluding the pendulum, along with their corresponding raw values from the HX711 module during static loading, were used to determine the system's calibration curve through linear regression, following the least squares method. The linear equation from this curve enables the inference of the vertical load applied at the free end of the beam as a function of time based on the raw signal values.

To simulate a dynamic load, mass V was dropped ten times, with the goal of theoretically estimating the peak dynamic load and comparing it with the value recorded by the data logger. The calculation was based on the principle of energy conservation, assuming that the gravitational potential energy from the initial position of the mass is entirely converted into elastic potential energy stored in the beam at its maximum deflection.

$$k_{beam} = \frac{W}{\Delta y} = \frac{3EI}{\ell^3} \quad (2)$$

$$U_{gravitational} = mgh \quad (3)$$

Table 2. Known masses and calculated weights

Item	Known mass (kg)	Calculated weight (N)
Zero	0	0
I	3.008 ± 0.001	29.44 ± 0.01
II	2.989 ± 0.001	29.25 ± 0.01
III	1.596 ± 0.001	15.62 ± 0.01
IV	0.498 ± 0.001	4.87 ± 0.01
V	0.494 ± 0.001	4.83 ± 0.01
VI	0.499 ± 0.001	4.88 ± 0.01
I + II	5.997 ± 0.002	58.69 ± 0.02
I + II + III	7.593 ± 0.003	74.31 ± 0.03
I + II + III + IV	8.091 ± 0.004	79.18 ± 0.04
I + II + III + IV + V	8.585 ± 0.005	84.02 ± 0.05
I + II + III + IV + V + VI	9.084 ± 0.006	88.90 ± 0.06
Pendulum	0.413 ± 0.001	4.04 ± 0.01

Source: author**Table 3.** Values used on calculations

Item	Symbol	Value	Unit
Gravity	g	9.7864	m s^{-2}
Elasticity modulus	E	2.07×10^{11}	Pa
Beam length (between the fixture and the hook bolt)	ℓ	0.36	m
Beam area moment of inertia	I	1.1×10^{-8}	m^4
Impact release height	h	0.1	m
Beam stiffness	k	146412	N m^{-1}
Pendulum release angle	θ_0	45	deg

Source: author

$$U_{elastic} = \frac{1}{2}k\Delta y^2 \quad (4)$$

$$U_{gravitational} = U_{elastic} \quad (5)$$

$$mgh = \frac{1}{2}k\Delta y^2 \quad (6)$$

$$\Delta y = \frac{W}{k} = \frac{load_{max}}{k} \quad (7)$$

$$mgh = \frac{1}{2}k \left(\frac{load_{max}}{k} \right)^2 \quad (8)$$

$$load_{max} = \sqrt{2mghk} \quad (9)$$

To generate a consistent dynamic load, a pendulum was used. Knowing the mass and initial angle of the pendulum, it was theoretically possible to determine the maximum vertical load, which occurs at the lowest point of its trajectory, when all the gravitational potential energy is converted in kinetic energy. This procedure was repeated seventeen times in sequence. The mass was released from an initial angle of forty-five degrees and allowed to swing until completing two full cycles, resulting in four load peaks. Calculations were based on the principle of energy conservation.

$$K = \frac{1}{2}mv^2 \quad (10)$$

$$v = \sqrt{2gh} \quad (11)$$

$$h = L(1 - \cos \theta_0) \quad (12)$$

$$v = \sqrt{2gL(1 - \cos \theta_0)} \quad (13)$$

$$T_{max} = W + F_{centripetal} \quad (14)$$

$$T_{max} = mg + \frac{mv^2}{L} \quad (15)$$

$$T_{max} = mg + \frac{m2gL(1 - \cos \theta_0)}{L} \quad (16)$$

$$T_{max} = mg(3 - 2 \cos \theta_0) \quad (17)$$

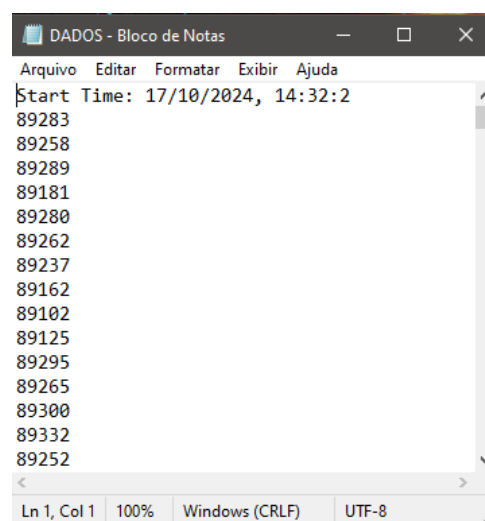
Figure 19. Pendulum setup

Source: author

2.4 Data Collection and Analyses

For data collection, a micro SD card formatted with FAT32 was used to enable communication with the Arduino. The memory card was cleared before each use to prevent new logs from being appended to existing files. Logging began upon connecting the power supply with the card inserted, and the first line recorded the start date and time, capturing data at 80 samples per second (SPS). Pressing the Arduino reset button restarted the process, logging the new date and time. An example of the file's contents is shown in Figure 20.

The Arduino code is presented in Appendix A. This code reads raw values from the HX711 at 0.0125-second intervals, achieving a total of 80 SPS. Data is stored in dynamic memory and transferred to the SD card once per second, a technique known as buffering.

Figure 20. Raw data registred

Source: author

Some strategies were applied to analyze the data, starting with outlier correction in the raw values. Certain points on the graphs were visibly inconsistent, complicating data visualization. A simple filter was used to flag points outside a defined range, which was set based on the minimum and maximum values needed to keep the plotted sequence visually continuous. Outliers identified were replaced by their preceding value to improve data presentation on the graphs. However, after this correction, the set of points near each outlier was excluded from result calculations.

During the static loading calibration process, for each load, three seconds of the most stable signal segment were selected from the graphs. This provided 12 points for the calibration curve (11 from known loads and 1 from no load). Each of these points was calculated from 240 values, using the mean and mean absolute deviation. After calibration, graphs were plotted using predicted load (N) versus time (s); previously, raw values from the HX711 were used instead of predicted loads.

For collision testing, only the highest logged value from each impact was used, with the mean and mean absolute deviation of all values calculated to compare with the predicted value; only one test were not included. For the pendulum testing, which produced four load peaks per release, the highest value from the fourth peak was used, as the load measurements became smoother. Similarly, the mean and mean absolute deviation of these peak values were calculated for comparison with theoretical predictions. In the pendulum case, some tests were excluded due to outliers or irregular sequences where the four consecutive peaks did not decrease as expected.

3 RESULTS

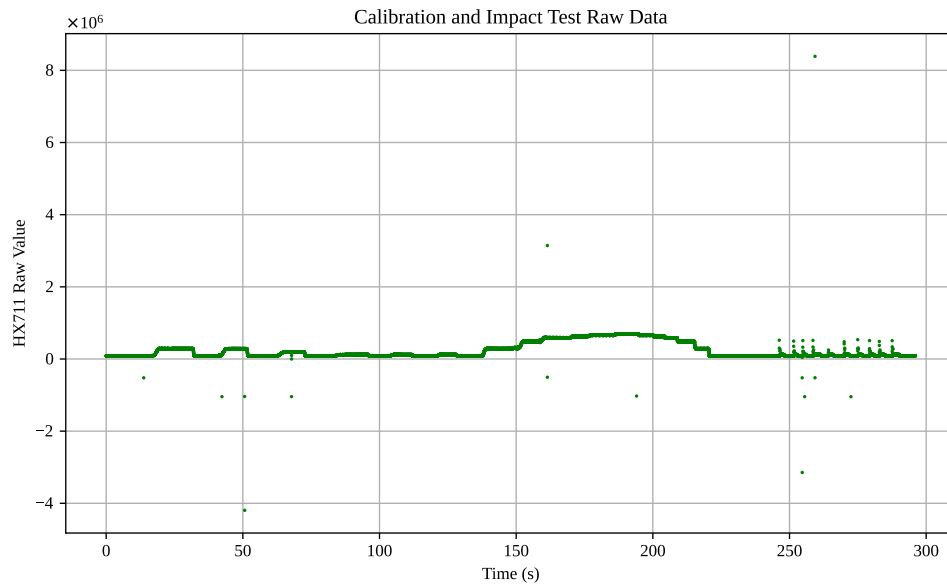
The results of the experiments consist of approximately 10 minutes of raw data from the HX711 module. Initially, the data is expressed as raw values over time. After filtering and converting, it reflects the vertical load applied to the hook bolt at the end of the tube. The detailed data collected and used for evaluation is presented in Table 4. The Figures 21 and 22 show the graphs with raw values, both with and without outliers.

Table 4. Collected data

Experiment	Number of points collected	Elapsed time (s)	Number of outliers	Percentage of outliers (%)
Calibration and impact	23680	298	17	0.0718
Pendulum	14160	177	12	0.0847

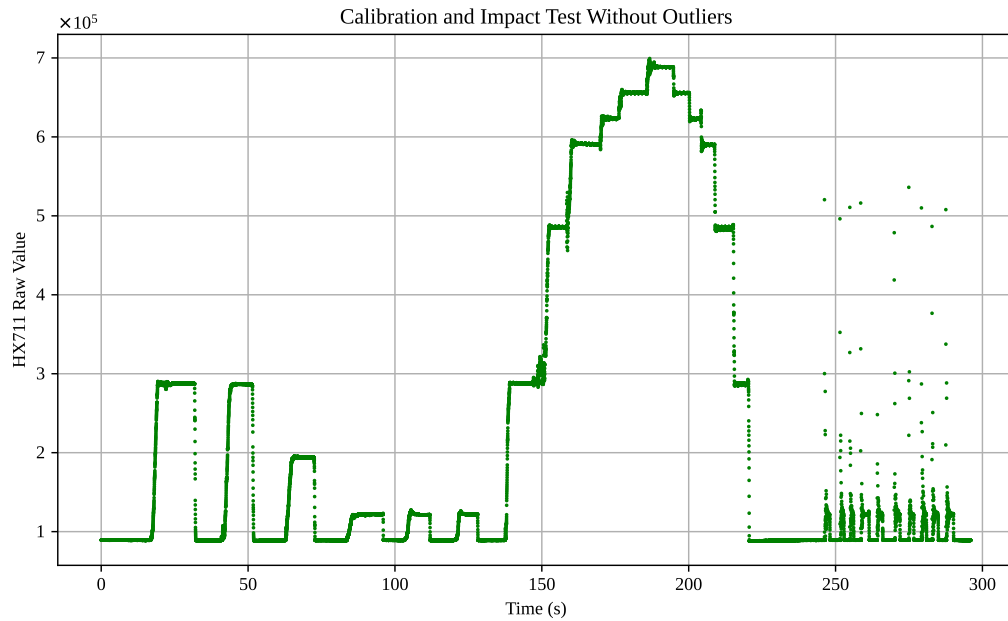
Source: author

Figure 21. Raw experience data



Source: author

The comparison between the graphs before and after outlier exclusion, between Figures 21 and 22 and between Figures 26, and 27, shows that, despite the small number of outliers, they significantly compromise the clarity of information in the graph. The low percentage of outliers indicates that the developed system is reliable, but issues arise with outlier identification. In this study, identifying them was straightforward since the expected signal behavior was known. However, in real applications, this might not be the case. Thus, it would be useful to investigate why these outliers occur and how to eliminate, reduce, or identify them more easily in data series.

Figure 22. Raw experience data without outliers

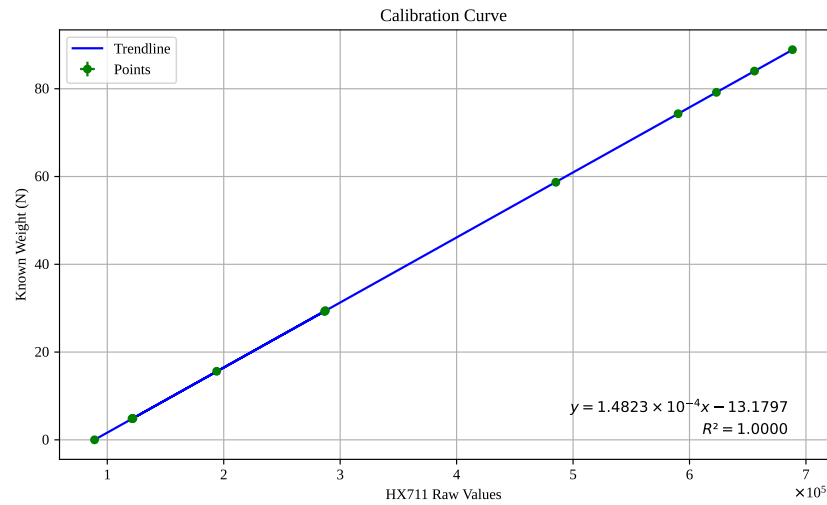
Source: author

The calibration curve was generated using 12 points, with values shown in Table 5. These points include the known weights and the average raw value over 3 seconds from the HX711 for each static load. The estimated error is represented by the mean absolute deviation. The Figure 23 displays the calibration curve and the equation for the trend line, which converts raw values to load values in Newtons.

Table 5. Calibration curve values

Item	Raw value from HX711	Calculated weight (N)
Zero	89050 ± 90	0
I	287300 ± 400	29.44 ± 0.01
II	286600 ± 100	29.25 ± 0.01
III	193960 ± 90	15.62 ± 0.01
IV	121930 ± 60	4.87 ± 0.01
V	121240 ± 70	4.83 ± 0.01
VI	121860 ± 60	4.88 ± 0.01
I + II	485200 ± 900	58.69 ± 0.02
I + II + III	590200 ± 500	74.31 ± 0.03
I + II + III + IV	623100 ± 500	79.18 ± 0.04
I + II + III + IV + V	655800 ± 400	84.02 ± 0.05
I + II + III + IV + V + VI	688400 ± 200	88.9 ± 0.06

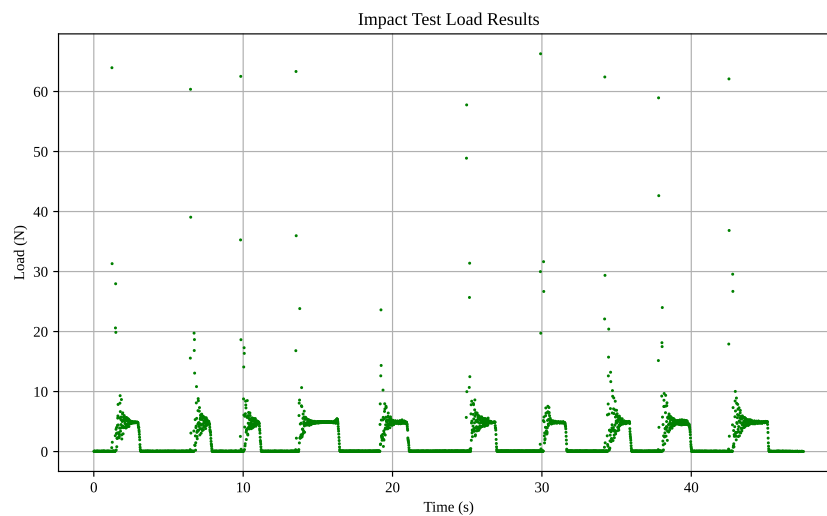
Source: author

Figure 23. Calibration curve

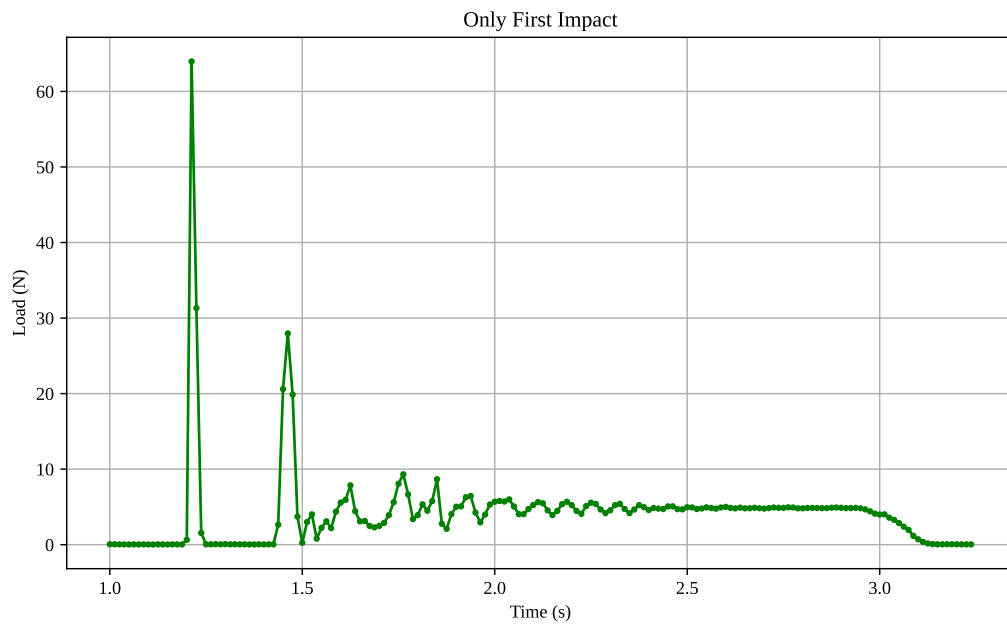
Source: author

The method used to determine values from logging static loads proved highly accurate, with the mean over three seconds used to calculate values and the mean absolute deviation as the estimated error. The errors are so minimal that they cannot be seen in Figure 23, which includes error bars. This accuracy is also indicated by the R-squared coefficient of determination from the trend line, with a value close to 1.

The data collected during the impact tests is presented in Figure 24. To aid understanding, Figure 25 includes only the results of the first impact. The peak load values recorded in each impact are listed in Table 6. The only value excluded from the mean calculation is from impact 5, which is highlighted in bold.

Figure 24. Impact dynamic load testing

Source: author

Figure 25. First impact**Source:** author**Table 6.** Impact results

Impact	Time (s)	Load (N)
1	1.2125	63.97
2	6.4750	60.37
3	9.8375	62.53
4	13.5375	63.34
5	19.2250	23.61
6	24.9625	57.77
7	29.9125	66.29
8	34.2125	62.42
9	37.8125	58.95
10	42.5250	62.10
Mean	-	62 ± 2

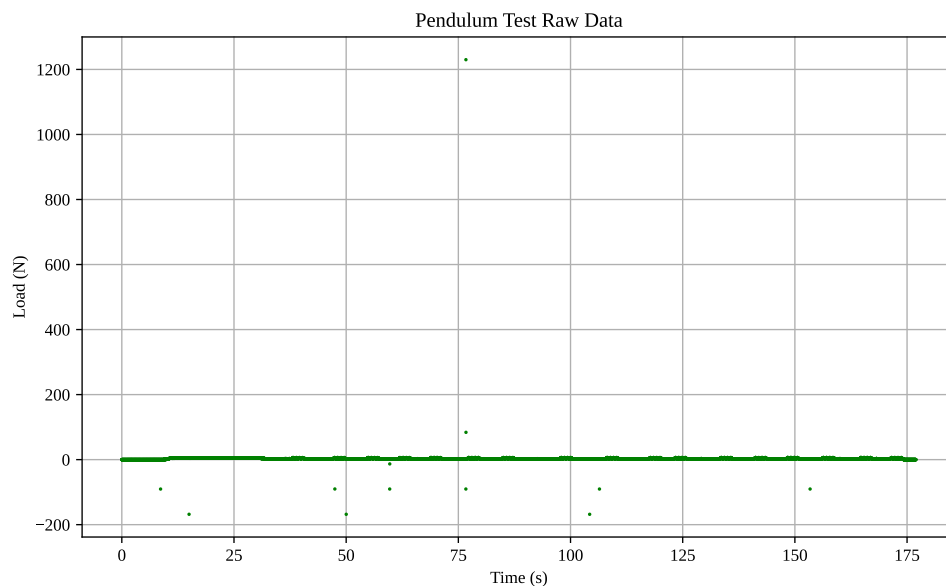
Source: author

The data collected during impact testing, shown in Figure 24 and Table 6, closely represents the expected load behavior. The main issue, however, is the discrepancy between theoretical and experimental load peaks, which will be discussed later. For these tests, a half-filled Coke™ bottle was dropped from 10 cm. The bottle bounced before stabilizing, which is clearly visible in the results, especially in Figure 25. This bottle, referred to as mass V, weighs about half a kilogram, and once stabilized, the load registered is about 5 N.

In a simplified, qualitative way, it is coherent to imagine that if your hand is on a table and a 0.5 kg mass is dropped from 10 cm, the maximum force you would feel would be approximately 60 N, equivalent to a static load of a 6 kg mass. However, despite the challenges posed by these unpredictable and highly variable loads, using a pendulum system provides a smoother alternative.

In the pendulum tests, graphs with and without outliers are shown in Figures 26 and 27. For clarity, Figure 28 presents data recorded only during the 16th pendulum release. Several data points were excluded from the mean calculation; these are highlighted in bold in Table 7, specifically values from releases 2, 5, 6, and 14 due to outliers, and from releases 3, 4, 10, 12, and 13 due to sequences of peak values without expected decreases.

Figure 26. Pendulum dynamic load testing

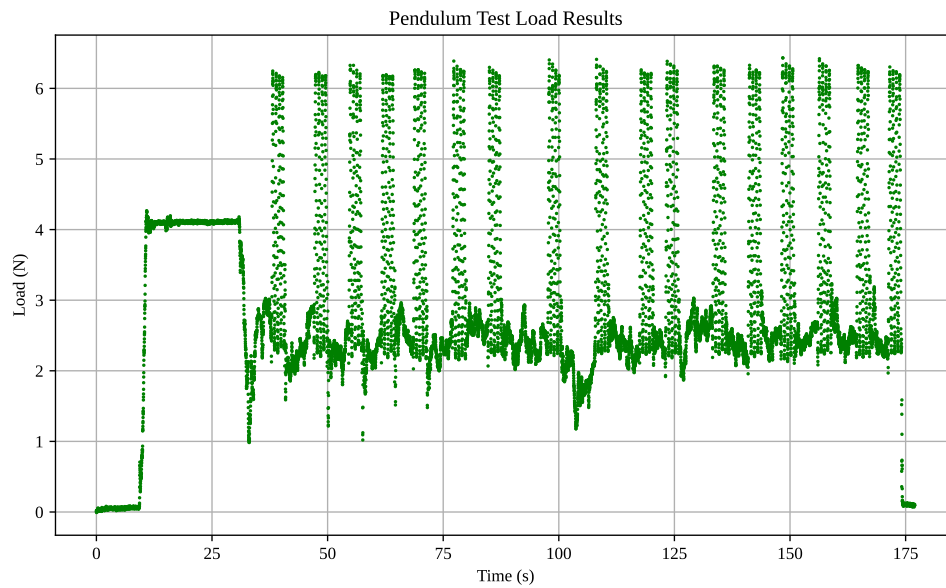


Source: author

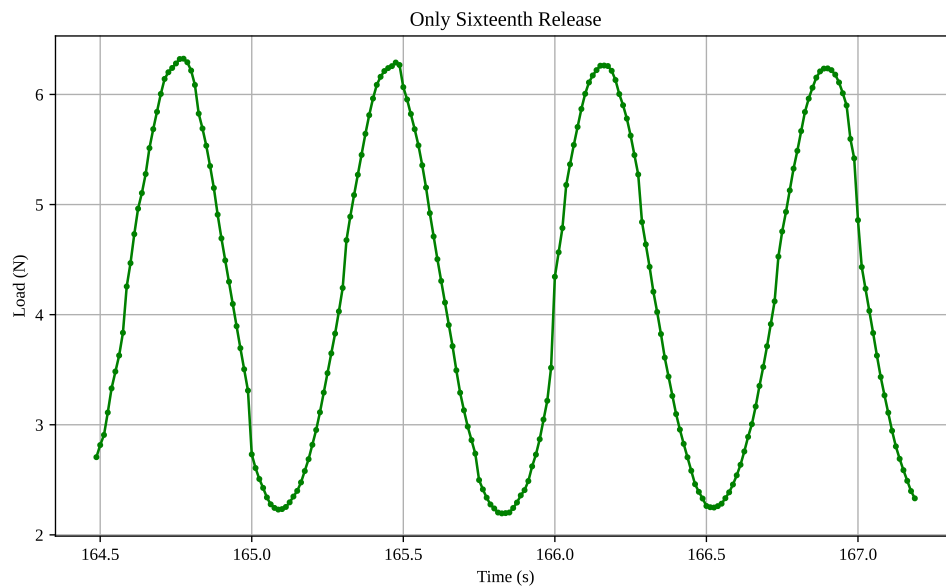
The Figure 28 illustrates the behavior of pendulum loads, showing two complete cycles. Load peaks occur at the pendulum's lowest trajectory point, and lower loads occur at higher points. The pendulum allows a smoother and more predictable dynamic load, which depends only on mass, gravity, and release angle. Despite these advantages, about half of the results, those highlighted in bold in Table 7, were not considered.

Only the first load peak was used for result calculation, as it is the closest to the desired release angle, but the following four peaks were checked for consistency. This was done because secondary oscillations, which interfered with results, were noted after pendulum release. Since the pendulum's natural tendency is to decrease amplitude over time, only releases where this trend was observed were considered.

The Table 8 presents the final results calculated with the selected data. And Table 9 presents some specifications of the system of this works and others.

Figure 27. Pendulum dynamic load testing without outliers

Source: author

Figure 28. 16th pendulum release

Source: author

Table 8 highlights a large difference between theoretical and experimental results in the impact case, indicating that the theoretical analysis used is inadequate, likely because it overlooks the impact characteristics, such as contact time and damping coefficient. An alternative approach could have been applied, as the cantilever beam is a straightforward model with ample setup data, allowing certain approximations. However, with the car chassis, such approximations wouldn't be feasible, so changing the source of dynamic loads proved to be a more practical solution.

Table 7. Pendulum results

Release	Time (s)	Load peak 1 (N)	Time (s)	Load peak 2 (N)	Time (s)	Load peak 3 (N)	Time (s)	Load peak 4 (N)
1	38.1375	6.25	38.8875	6.21	39.5750	6.18	40.2750	6.15
2	47.4375	6.20	48.1125	6.23	48.8625	6.18	49.5750	6.18
3	54.8750	6.33	55.6000	6.33	56.3125	6.26	57.0250	6.21
4	61.9625	6.18	62.6750	6.19	63.3875	6.17	64.0625	6.17
5	68.9000	6.26	69.5875	6.26	70.2750	6.23	70.9875	6.21
6	77.3000	6.39	78.0000	6.31	78.7500	6.27	79.4500	6.24
7	85.0125	6.30	85.7500	6.26	86.4500	6.22	87.1500	6.18
8	97.9500	6.40	98.6625	6.34	99.3625	6.26	100.0750	6.18
9	108.1750	6.41	108.9250	6.31	109.6125	6.27	110.3125	6.24
10	117.8375	6.26	118.5250	6.22	119.2375	6.20	119.9750	6.21
11	123.4625	6.38	124.1625	6.34	124.9000	6.32	125.6000	6.25
12	133.6125	6.31	134.3000	6.32	135.0125	6.28	135.7500	6.26
13	141.2750	6.33	142.0000	6.23	142.7125	6.26	143.4250	6.22
14	148.4625	6.43	149.1750	6.35	149.9125	6.32	150.6125	6.28
15	156.3875	6.42	157.0875	6.35	157.8250	6.32	158.5375	6.26
16	164.7750	6.32	165.4750	6.29	166.1625	6.26	166.9000	6.24
17	171.6125	6.30	172.3125	6.25	173.0125	6.24	173.7500	6.19
Mean	-	6.35 ± 0.06	-	6.29 ± 0.04	-	6.26 ± 0.03	-	6.21 ± 0.04

Source: author

Table 8. Final results

Experiment	Experimental value (N)	Theoretical value (N)	Percentage error (%)
Impact load peak value	62 ± 2	376	84
Pendulum load peak value	6.35 ± 0.06	6.41	0.94
Pendulum estatic load (weight)	4.106 ± 0.08	4.04 ± 0.01	1.6

Source: author

Table 9. Data logger systems velocity and price

System origin	SPS (s^{-1})	Price (USD)
This work	80	25
Hemeda 2017	20	25
Silva 2019	80	45

Source: <https://www.aliexpress.com>

The pendulum test results demonstrate that the system works: the percentage error is below 1%, and the calculated values fall within the range of experimental values and the predicted error, attesting to its accuracy. The same holds true for the static load of the pendulum weight, albeit with a slightly higher percentage error.

4 CONCLUSION

Considering the low cost compared to conventional systems and the accuracy achieved during model testing, using Arduino to create a strain gauge data logger offers great potential for data collection on an Formula SAE team car. This setup could be used to validate design and manufacturing processes, providing far greater insights than this study explored.

Unfortunately, testing the system on the actual car chassis, or with the car in motion, was not feasible, which was the objective and motivation for this study. However, the gathered information and experience provide a solid foundation for future research. The system developed proved cheaper than that in Silva *et al.* (2019) and faster than Hemeda, Aboukarima, and Minyaw (2017), which is a significant advantage.

4.1 Recommendations for Future Research

The system used in this work demonstrated some limitations that could be addressed in future studies. The HX711 board is designed primarily for load cells, commonly applied in basic scales, where the sampling rate is not a critical factor. However, in Formula SAE applications, strain gauges can potentially be used to measure vibrations if the sampling rate is sufficiently high (Riley; George, 2002).

One strategy to increase the sampling rate would be to use alternative ADC and INA circuits. A suggested approach is to purchase a commercial circuit; otherwise, if a custom circuit is used, it is essential to ensure a high-quality assembly. This is particularly important as prototype boards, like the ones used here, tend to have issues with frequent use, such as poor connections at wiring points.

Implementing a buffer was a crucial development in the data logger's design. Previously, the sampling rate was highly unstable and unpredictable. The Arduino board's limited RAM and processing capacity can easily be improved by using an ESP32 board, which remains affordable. However, in the present system, the HX711 ultimately limited the sampling rate. The buffer essentially collects data in packets, storing a set number of values in RAM before opening the SD card and saving the entire packet at once. This approach reduces processing load and minimizes the risk of data loss.

Another important observation during this project was that the unpredictability of the team's schedule posed a greater challenge than technical issues when testing the system on the car chassis. Effective management tends to provide the highest returns with the least investment.

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APPENDIX A . ARDUINO CODE

```
#include <SD.h>
#include <SPI.h>
#include "HX711.h"
#include "RTCLib.h"

const int hx711_dout = 2;
const int hx711_sck = 3;
const unsigned long interval = 1000 / 80; // 80 samples per second

HX711 scale;
File Dados;
RTC_DS1307 rtc;

long buffer[80]; // Buffer for 80 samples (1 second at 80 sps)
int bufferIndex = 0;
unsigned long previousMillis = 0;

void setup() {
    Serial.begin(9600);

    // SD Card setup
    if (!SD.begin(10)) {
        Serial.println("SD init failed");
        return;
    }

    // RTC setup
    if (!rtc.begin()) {
        Serial.println("RTC init failed");
        return;
    }

    if (!rtc.isrunning()) {
        rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
    }
}
```

```

// Initialize the HX711 scale
scale.begin(hx711_dout, hx711_sck);

// Write start time to the file in CSV format
DateTime now = rtc.now();
Dados = SD.open("Dados.txt", FILE_WRITE);
if (Dados) {
    // Write start time as CSV: day/month/year, hour:minute:second
    Dados.print("Start Time: ");
    Dados.print(now.day(), DEC);
    Dados.print('/');
    Dados.print(now.month(), DEC);
    Dados.print('/');
    Dados.print(now.year(), DEC);
    Dados.print(", ");
    Dados.print(now.hour(), DEC);
    Dados.print(':');
    Dados.print(now.minute(), DEC);
    Dados.print(':');
    Dados.print(now.second(), DEC);
    Dados.println();
    Dados.close();
} else {
    Serial.println("Failed to open file for start time");
}

void loop() {
    unsigned long currentMillis = millis();

    // Capture data at 80 samples per second using millis
    if (currentMillis - previousMillis >= interval) {
        previousMillis = currentMillis;

        // Read raw value from HX711
        long rawValue = scale.read();
        buffer[bufferIndex++] = rawValue;

        // If buffer is full, write data to SD card in CSV format

```

```

    if (bufferIndex >= 80) {    // 1-second buffer (80 samples)
        writeBufferToSD();
        bufferIndex = 0;    // Reset buffer
    }
}

// Function to write the buffer to SD card in CSV format
void writeBufferToSD() {
    Dados = SD.open("Dados.txt", FILE_WRITE);
    if (Dados) {
        // Write 1 second of data (80 samples) as raw values in CSV format
        for (int i = 0; i < 80; i++) {
            Dados.println(buffer[i]);
        }
        Dados.flush();    // Ensure data is written to the card
        Dados.close();
        Serial.println("Buffer written to SD card");
    } else {
        Serial.println("Failed to open file for data write");
    }
}

```