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Project: Team 16, Structurally Integrated Sensing System for Automotive Crash Analysis

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1. Abstract

This project addresses the time inefficiencies of current methods used to assess post-crash vehicle deformation by developing a structurally-integrated system for immediate data acquisition. Sponsored by Shape Corp., a leading automotive supplier, our goal was to reduce the time and resources required to quantify the structural deformation sustained by a vehicle after a collision. Focusing on existing sensors and methods, we developed and tested a sensing system integrated onto a structural component provided by Shape Corp. The desired outcome is an innovative solution that delivers structural deformation data within four minutes of a car crash, streamlining the crash investigation process.

2. Project Introduction, Background, and Information Sources

i. Project Sponsor: Shape Corp.

- Tier 1 automotive supplier founded in 1974 [1]
- Specializes in innovative and lightweight body-in-white and structural components for the automotive industry
- Received recognition from customers including Toyota [2] and General Motors [3]
- Engineering services [4]
    - Product development
    - Product design
    - Testing

        - Quasi static testing
        - Low-speed crash tests
- Manufacturing services [5]
    - Industry-leading roll-forming processes
    - World-class welding services
- Advanced Product Development team is always looking to innovate their products [6]
    - Wishes to stay ahead of the market and maintain their competitive edge
    - Identifies unmet needs through market analysis and technical research
    - Develops cutting edge solutions to incorporate into their products
- **Currently, they have identified the need for a shortened time frame to receive data about the deformation response of vehicle structural components in a collision.**
    - Useful during quasi static and crash testing that Shape corp. performs to improve its products
    - Aids in reconstruction of vehicle crashes for forensic or insurance purposes

ii. Current Alternative Methods

Currently, there are multiple techniques to reconstruct an accident to understand the damage done to a vehicle. These methods are outlined in **Table 2.1**, pg. 4.

Table 2.1: Current Alternative Methods to Understand Damage Done to a Vehicle

Method	Description	Advantage	Disadvantage
1. Event Data Recorder Downloads	"Retrieve and interpret data recorded during a passenger-car crash event… including but not limited to vehicle speed, acceleration, throttle position, break application, steering wheel angle, seat belt use, and airbag deployment." [7]	Do not have to be performed at the scene of the accident.	- Specific tool dedicated to EDR data retrieval may be needed to obtain data from the device. - Does not include deformation values or structural information.
2. Total Station surveying	Involves "shooting the total station at a prism [on] a pole…[and] marking the location of evidence with the bottom of the pole" [8]	Less expensive than 3D scanners while still providing detailed distance measurements [8]	- Requires at least 2 people to operate - Limited by visual obstacles - Requires post-processing
3. 3D Scanning	Involves "[emitting] a laser beam at a vertical range [excluding] the area below the scanner… The laser beam is then reflected back to the scanner by objects in its path." [8]	Data is accurate to a degree that it is permissible for artifacts in court cases [9]	- Equipment is expensive - post-processing is memory intensive and time consuming

3. 3D scanners generate point clouds that can be used to create a mesh, which can then be used for performing digital measurements and determining geometrical features or deformation. Many 3D scanners use photogrammetry in conjunction with the point cloud data to create realistic models of the scene being recorded.

3. Design Process

This section provides an overview of our current design process model, shown in **Figure 3.1**, pg. 5, and identifies its various features and justifications. We review the considerations that were made when developing our design process, and we compare this to the general ME 450 design process introduced this semester.

i. Design Process Overview

- Problem-oriented
  - Focused on abstracting & analyzing the problem before generating solutions [10]
- Primarily stage-based
  - Consists of a linear, chronological structure [10]
  - Each stage or sub-stage builds iteratively on the last
- Secondarily activities-based
  - A cyclical reworking process [10] is possible in some situations
  - Our process involves repeating previous stages if rework is needed

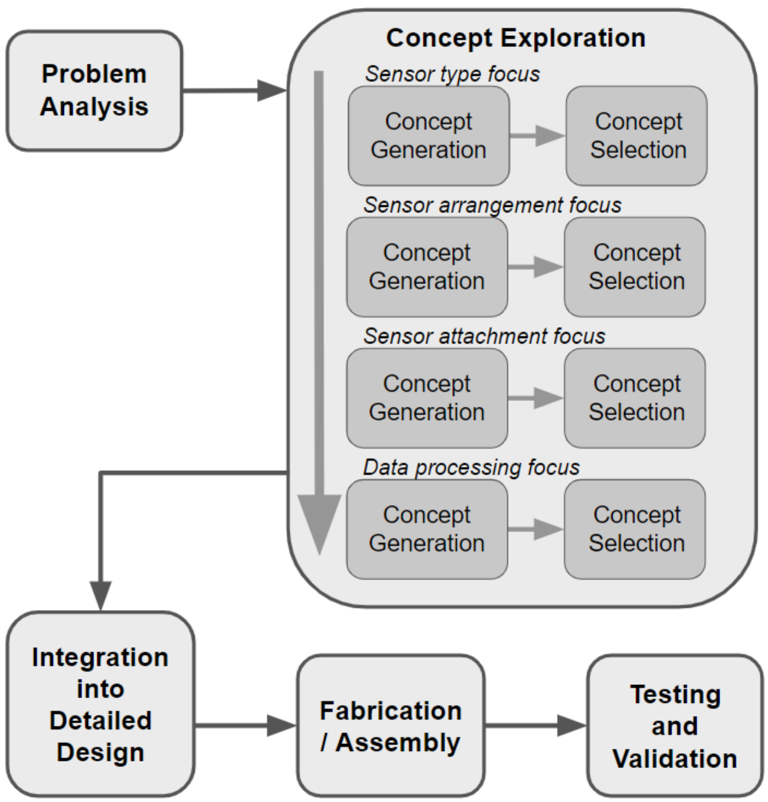


Figure 3.1: Our current design process model to develop the sensing solution.

ii. Design Process Stages

- Problem Analysis
  - Focuses on a full consideration of our problem

    - Generating a set of requirements & specifications for our design (**Table 5.1**, pg. 11)
    - Researching current solutions for benchmarking our design (**Table 2.1**, pg. 4)
    - The goal is to build a set of concrete objectives with which we can assess the viability of our potential solutions
- Concept Exploration
    - We have elected to conduct our concept exploration in multiple iterative sub-stages, as our project consists of a set of discrete design decisions, with each decision depending on the last
        - Sensor type focus: choose the specific sensor that best fits our needs
        - Sensor arrangement focus: decide how sensors will be positioned on our component
        - Sensor attachment focus: determine the best way to physically attach our sensors to the component
        - Data processing focus: devise an algorithm to effectively process our data and obtain useful information
    - *Concept Generation Sub-stage*
        - Research the components and forms that may be incorporated into our design in order to build a range of possible solutions
    - *Concept Selection Sub-stage*
        - Critically evaluate the solutions we conceptualize in the concept generation stage
        - Determine how effectively they can meet the requirements of our problem
        - Narrow our range of solutions to build upon or validate in later stages
- Integration into detailed design
    - Determine optimal spacing of sensors
    - Define exact vertical and horizontal placements on the bumper component
- Fabrication/Assembly
    - Physically building our design
    - Attaching sensors onto the bumper component
    - Wiring the system to the data acquisition system
- Testing and Validation
    - Determine our design's viability as a solution to the problem
    - May involve an iterative process for fine-tuning our design, involving returning to previous integration or concept exploration steps

iii. Design Process Considerations

- Problem-based rather than solution-based [10]
    - Our solution space involves making fundamental design decisions early in the design process

    - These will be hard to change later
    - We want to fully consider the problem definition and solution space before making design decisions
    - A solution-based design process model would require us to fully conceive of a solution at the start and then make subsequent changes to it [10]
    - This would discourage fundamental shifts from our initial design later in the process (which would be expensive)
- Primarily Stage-based
    - Involves constructing a design in a discrete set of stages which each build on the last [10]
    - Due to the nature of our solution space, we must make several discrete design decisions that each build on the previous decision
        - Sensor type
        - Sensor positioning/arrangement
        - Sensor attachment
        - Data processing algorithm
- Secondarily activity-based
    - Involves repeating a set of tasks cyclically, reworking and improving the concepts of a design over time [10]
    - Our process leaves room to repeat parts of our process if rework is needed
    - We will return to previous stages if concept selections cannot be adequately made from our generated concepts, or to make design changes from the validation stage.
    - Theoretically, we may cycle through stages several times before moving on

iv. Comparison to Other Design Processes

- Cross's model of the design process [11]
    - Inspiration of the general structure of our design process model
    - Similarly starts with an exploration of the problem space
    - Moves on to concept generation and evaluation tasks
    - Also proposes returning to earlier stages similar to activity-based models
    - Our model diverges by using multiple separate concept generation and evaluation stages
- ME 450 Design Process [12]
    - Similar in its general structure and order
    - Both start with an identified need and proceed with a problem definition phase
    - Both culminate in a solution development and verification phase
    - Our concept generation stage involves multiple concept exploration and selection phases not included in the 450 Design Process Model
    - Our design process starts from fundamental decisions and builds on them iteratively with following decisions, increasing in specificity

4. Design Context

This section considers the broader context that will influence our sensing system's design, the use of it, and the eventual effects of its implementation on society and various groups. It describes the various stakeholders, the social impact, and the sustainability of the design, and the role of intellectual property, ethics, power dynamics, and inclusivity in our project.

i. Stakeholders

Our design has the ability to affect many stakeholders beyond the scope of our project. A map detailing primary, secondary, and tertiary stakeholders can be seen below in **Figure 4.1**, pg. 9.

ii. Stakeholders Positively Impacted

- Shape Corp.
  - Can gain a competitive advantage in the automotive industry
  - Can profit in the future from the successful development of the sensing system
- Automotive Safety Research Organizations and Manufacturers
  - Obtain valuable data for comprehensive understanding of vehicle impacts
  - Can identify deflections and loads on specific components
- Emergency Responders and End Users (Car Owners)
  - Can use the system's data to corroborate the accuracy of an innocent driver
  - Improved safety features derived from sensing system's data

iii. Stakeholders Negatively Impacted

- Industries Relying on Extended Timeline for Crash Data
  - Reduced demand for their services (may disrupt their current business model)
- Direct Competitors
  - Loss of business as Shape Corp. gains competitive edge
- Other Automotive Component Manufacturers
  - Could face challenges modifying designs to integrate the new sensing system
  - Could introduce additional design constraints to the already complex process of creating car components
- Workers in Sensing System Manufacturing
  - Potential negative impacts (poor working conditions) depending on sourcing
- Skeptics Concerned with Data Privacy
  - Could raise debates about law enforcement access and driver consent [13]

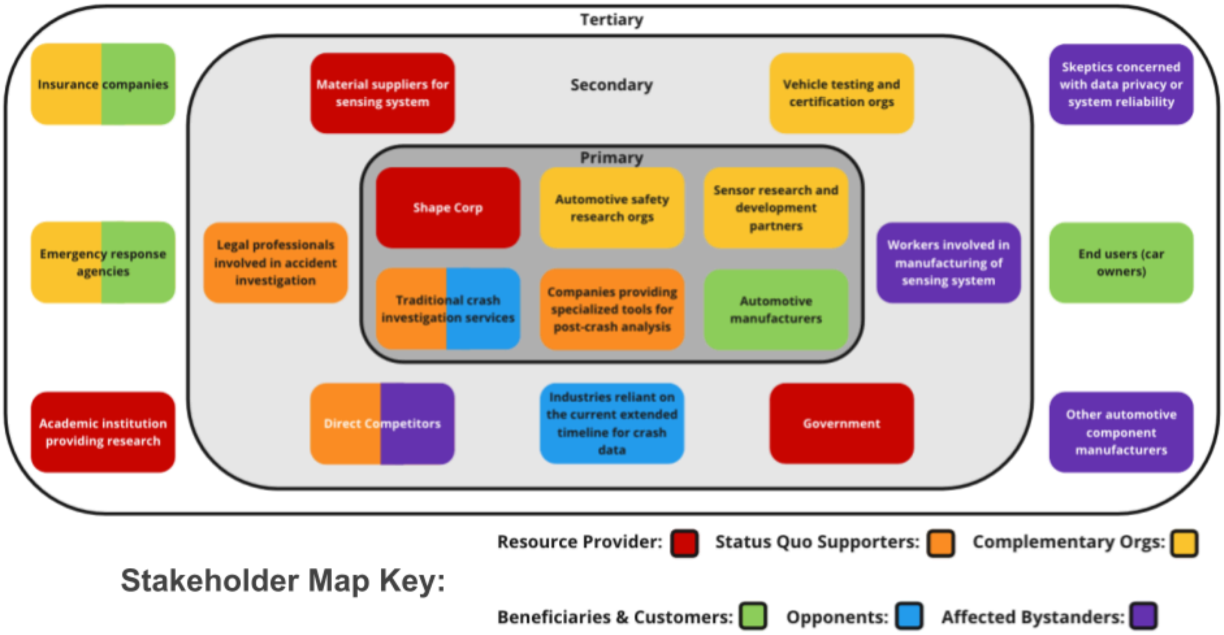


Figure 4.1: This figure shows a map depicting the various stakeholders that could be affected or influenced our sensing system's design. Primary stakeholders are those directly affected by the problem or implementation of a solution, secondary stakeholders are those outside of the direct context of the problem receiving no direct benefit from a solution, and tertiary stakeholders are those outside of the immediate problem but can influence the solution or problem space in the future.

iv. Social Impact and Sustainability

- Societal Aspects Driving the Project
  - Enhancing vehicle safety through greater understanding of crash absorption, improving future designs and manufacturing
  - Improving post-accident processes
    - Potential to enhance emergency response time by transmitting crash details instantly to first responders [14]
  - Reducing the economic impact of crashes (cost U.S. $340 billion in 2019 [15])
- Project Sponsor's Priorities
  - Prioritizes safety, profit, education over social impact initially
  - Innovation, profitability, and positive social impact through product sales
  - No hard price cap for our system, but cost-effectiveness preferred
- Enhancing Sustainability
  - Selecting materials with a reduced environmental footprint
  - Ensuring system minimally affects the car's overall energy consumption
- Reducing Pollutants
  - Opting for local shipping to reduce pollutants compared to worldwide shipping

- Potential Ethical Dilemma
    - Sponsor possibly prefers a less sustainable but cost-effective component
    - Plan to systematically assess advantages and disadvantages, engaging in dialogue to emphasize sustainability

v. Intellectual Property and Ethical Considerations

- Intellectual Property Agreement
    - Entered agreement with Shape granting them rights to the created sensing system
    - Need explicit permission to share information with people not directly involved
- Common Ethical Values Among Our Team, Sponsor, University, and Future Employers
    - Integrity, professionalism, diligence, and collaboration
    - Respect for intellectual property
    - "Hold paramount the safety, health, and welfare of the public" [16]
- Differing Emphasis on Sustainability and Social Impact
    - Private business potentially prioritize profit over environmental & social concerns
    - Shape Corp. does value social impact: it has an inclusion advisory board [17]
    - "Shape is committed to a sustainable future by manufacturing products in ways that limit our negative impact on the environment" [18]

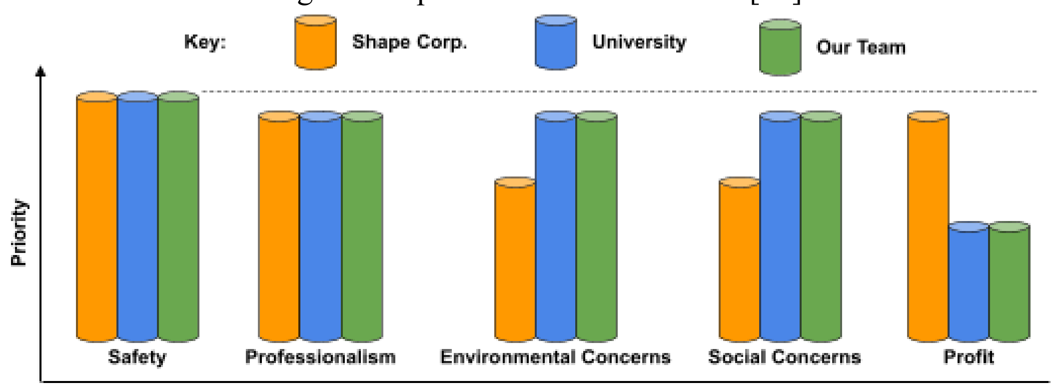


Figure 4.2: This chart depicts the differences and similarities in ethical concerns of Shape Corp., the University of Michigan, and our team. We all agree that safety and professionalism are a top priority, but differences may arise when it comes to the environment, social concerns, and profit. Because Shape Corp. is a private business, it is in its best interest to make a profitable product; in doing so, it may prioritize profit over environmental or social concerns. This is not to say Shape Corp. does not value inclusion and sustainability because it does have an inclusion advisory board [17], and publicly states it wants to reduce its negative environmental impact [18].

vi. Power Dynamics and Inclusivity

- Project Sponsor
    - Holds visible power over team by setting project goals
    - Holds hidden power by supporting the project financially

- Project Team

    - Holds visible power over sponsor by adhering to university processes & timeline
    - Holds invisible power over end users through team's perception of who the end users are and what they want
    - Within the team, members with expertise can subtly influence the project direction (invisible power)
- Addressing Power Dynamics Within the Team
    - Established open lines of communication
    - Encouraged team members to express opinions and concerns
    - Cultivated a culture of transparency and open-mindedness
- Strategies for Inclusivity
    - Engaging regularly with sponsor to meet Shape Corp.'s requirements
    - Transparent communication about internal deadlines and deliverables
    - Consider seeking external feedback from stakeholders not directly involved in the project to identify potential blind spots and address other inclusivity problems

By actively addressing power dynamics and promoting inclusivity, our team can ensure diverse perspectives are considered and create a more inclusive and ethical project.

5. User Requirements and Engineering Specifications

This section discusses the stakeholder requirements that will guide our team's design process, as well as the corresponding engineering specifications. These specifications, outlined in **Table 5.1**, pg. 11, will quantify the outlined requirements and allow us to validate the effectiveness of our design to ensure that the needs of the user and other stakeholders are met.

Table 5.1: Requirements and Engineering Specifications

Requirement	Priority	Specification
Measures deflection of bumper structure after applied load	1	Sensors should measure the deflection of the bumper structure up to 100 mm in 1 mm steps. Obtains an accuracy of 25% to true deflection.
Withstand crush/bending force applied to the provided bumper structure	2	Survive a load range up to 50 kN.
Obtain sensor data from the part quickly after impact	3	Provide requested deflection data within 4 minutes of tested impact.
Operate in various environmental conditions experienced by a vehicle	4	Sensor should operate between -40 and 140 °F.
Install the sensor on the bumper structure with limited supplies	5	Tools needed for installation are limited to those provided with

and tools		purchase of sensor(s) and those available in University of Michigan machine shop. Use ≤1 type of adhesive.
Sensors should not compromise the space necessary for the existing sensors and parts connected to the bumper component.	6	Take up less than 15% of surface area available on the specified part. System should protrude <25 mm from the surface of the part.
Withstand temperature required for painting process*	7	Sensors will not be painted, but should withstand a continuous limit of 365 °F for one hour.
Sensor system should be reasonably cost-effective*	8	The total cost of the entire sensor system should be less than $500.
Sensor system should obtain force data under significant crash loads*	9	Determine the forces experienced up to 50 kN (in increments of 5 kN) at least three locations on the front bumper structure from the measured deflection data.*

*Not mandatory for project success but preferred by sponsor

i. Shape Corp. vs Team 16's Reqs & Specs

The relative importance of requirements is notated in the priority column of **Table 5.1** above, with requirements ordered based on what features must be included in the design to ensure functionality according to our problem statement and survival throughout the remainder of the automotive manufacturing process.

- Certain requirements and specifications were defined by our project sponsor through weekly meetings and external communication. These are requirements 1, 2, 3, 4, 7, 8, 9.
    - Requirement 1 is the most crucial for our project. Shape Corp. has provided us with the corresponding specification based on their industry experience and knowledge of their product's needs.
- Certain requirements were provided to us by our sponsor, but we were responsible for quantifying the specification.
    - Requirement 3 dictates that our system obtains sensor data relatively quickly. We determined that 4 minutes is a reasonable amount of time between the moment of impact and the moment useful data is provided.
- Other requirements and specifications were determined by our team based on our analysis of the problem.
    - These are requirements of priority 5 and 6. The specifications that elaborate on these requirements have been quantified by our team based on research and communication with our sponsor, though the specific values are currently being reviewed and updated based on further research.
    - There are no listed requirements that specify how long the system should take to implement into a full vehicle, as there may be changes to the installation and optimal placement of sensors in the system to serve multiple structural applications in different locations of a car.

These requirements listed above cover issues related to functionality, longevity, and environmental impact of the sensor system, as well as guide considerations towards factors that aren't necessarily required but should be discussed during the decision making process. It is possible that this set of requirements will change throughout the course of the project, but we feel that this list clearly defines our project's requirements with our current knowledge.

ii. Laws and Regulations Regarding Automotive Sensors

Many of the sensors that we've been researching specify that they've been used for automotive applications, so we believe the sensor selection portion of our project will not be hindered by any standards or laws. We will be reviewing Regulatory Standards for Automotive Safety such as ISO 26262 - Functional Safety for Road Vehicles, which discusses safety requirements for electrical and software-intensive systems in vehicles.

- ISO 26262 - Functional Safety for Road vehicles is significant to our project because of safety concerns associated with increased use of electrical systems in vehicles. This standard references the International Electrotechnical Commission 61507 standard to road vehicles, which emphasize consideration of environmental factors that could lead to unsafe situations for the electrical components in automotive vehicles [19].

iii. Wishes vs Requirements

- Requirement 7 is starred (*) and has a low priority because Shape Corp. confirmed for us that they could potentially install the sensor post-painting process if a sensor system that can withstand that environment cannot be found during our project timeline.
- Requirement 8 is starred to show that it is a wish and not a requirement because our sponsor has clarified that this project emphasizes research and learning, so we should focus on determining a system that will meet the goal without worrying about the cost of the model and testing. If this design is successful and adapted into general society, then the cost will decrease as a result of mass-production and large supply orders.
- Requirement 9 is starred as well because it is a desired secondary function of the sensor system to record force data following a large load impact. This is not required for us to complete as the main focus of our sensor system is determining deflection, but backing out force measurements would be appreciated if achieved.

6. Concept Generation & Development

Our concept exploration process consisted of three phases before we narrowed down our two alpha concepts. These phases were concept generation, concept development, and concept selection. We brainstormed a variety of ideas that could potentially solve our problem. Based on our wide array of ideas, we were able to determine three major functional requirements of a system. From these functional requirements, we narrowed down our ideas into a morphological chart of most feasible design choices.

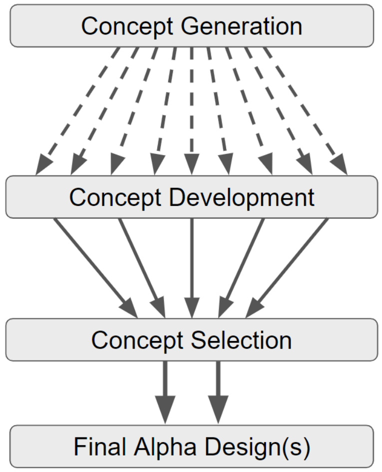


Figure 6.1: Concept exploration phase diagram.

i. Concept Generation

The first stage of our concept exploration process was concept generation. In this phase, each teammate compiled ideas spanning a large variety of approaches to solve our tasked problem. Without limiting ourselves by considering constraints or solution limitations too early in the process, ideas were brainstormed to generate a diverse spread of potential solutions. This initial concept generation was a form of individual brainstorming. These ideas were used as inspiration for the functional decomposition rather than a basis for it. Various sensor types were mentioned in this phase, regardless of whether we knew they would function for the task we had at hand, as well as various combinations of sensors and different sensor arrangements.

- Some concepts generated in this stage were:
    - (1) using carbon fiber sensors
    - (2) aligning sensors in a hexagonal array along one face of the bumper structure
    - (3) using radar sensors or acoustics to measure deflection
    - (4) attaching the sensors using nylon flex ties.

A more extensive list of concepts compiled during this process is located in **Appendix B**. We then used the 77 Design Heuristics [29] to build on our previous concepts to compile additional potential solutions. Some examples are:

- A sensor arrangement that spans 2 faces of the bumper (using design heuristic #54)
- A smart sensor with programmable capabilities for user customization (using design heuristic #9)
- Lining the sensors inside the bumper structure (using design heuristic #37)

Our group employed a functional decomposition brainstorming strategy for concept generation. We divided the design into various functions, generating numerous concepts for each category. These ideas stemmed from individual group members' initial designs and additional brainstorming, aiming to explore a broad range of ideas without initially considering feasibility or other constraints. A representation of this functional decomposition can be found in **Figure 6.2** on pg. 15 in the following section.

ii. Concept Development

Each of the categories in our functional decomposition had many concepts which had to be narrowed down based on their feasibility relative to our project requirements. We used various criteria to eliminate concepts such as:

- Specifications - Eliminated concepts were judged as not meeting certain project specs
  - Example: Pressure sensors were too weak (low force measurement range) to be used in our design, as they would have to measure direct impact forces.
- Cost - Eliminated concepts would be too costly to justify
  - Example: A hexagonal array of sensors would require many more sensors (significantly increasing cost) while not providing justifiably useful data.
- Experimental - Eliminated concepts were deemed too experimental or risky to pursue
  - Example: Carbon fiber sensors did not have enough information available on their properties or examples of past use to prove their reliability.

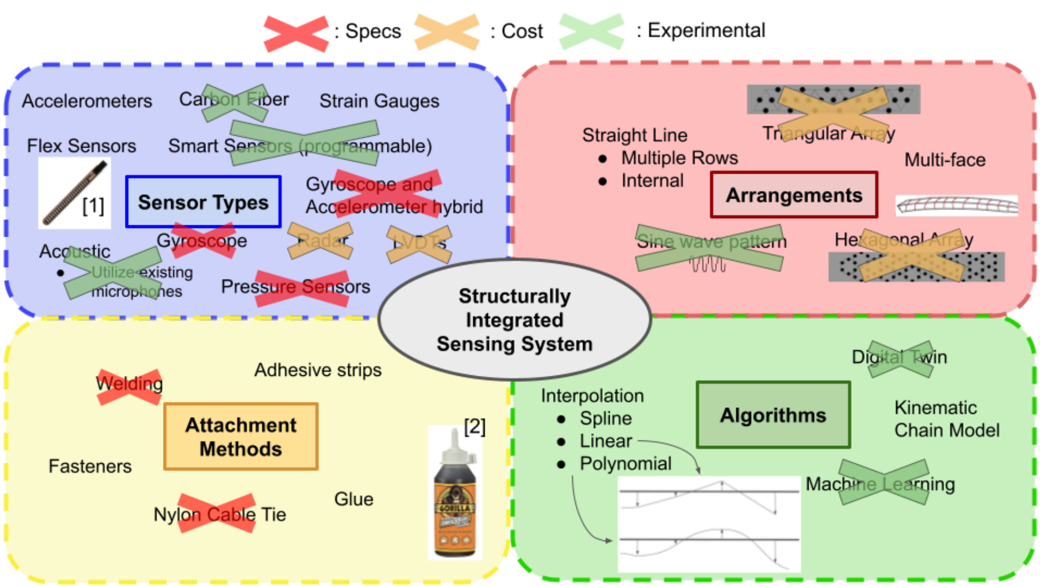


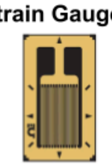
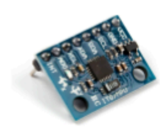
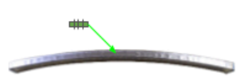
Figure 6.2: This shows a functional decomposition of the sensing system. Certain concepts were eliminated for not meeting specs, costing too much, or being too experimental.

We conducted preliminary analysis on certain concepts that we found to be more feasible after conducting additional research.

- Specific Concepts Eliminated:
    - LVDTs: These sensors, while precise, would be too expensive for our project, as communicated to us by our project sponsor.
    - Carbon Fiber Sensors: While these sensors were of interest because of their unique form factor, enabling them to be placed along a long section of the part, they were deemed to be too experimental for our purposes after conversations with our sponsor.
    - Pressure Sensors: These sensors would allow direct force measurement, however, after researching their specifications, would either not be strong enough to measure our expected forces or would be too large to integrate into our part.
    - Smart Sensors: These sensors incorporated an accelerometer and gyroscope with a built-in computer for data processing, however it would require a programming language we did not have experience with, which made it too experimental for us for further design consideration.

We conducted a morphological analysis to categorize our ideas into subcategories, ensuring a diverse set of solutions. Our concepts were organized based on sensor type, attachment method, and arrangement method. The sensing algorithm was omitted from the morphological chart due to its reliance on variables such as sensor data output and arrangement (linear versus staggered). Shape Corp. sought a range of diverse solutions, hence we excluded the algorithm from the morphological analysis to prevent its complexity from constraining potential designs. Exploring various combinations across these three categories led to 27 different design possibilities. Our morphological table can be seen in **Table 6.1** below.

Table 6.1: Morphological Chart of Sensing System

Sensor Type	**Strain Gauges**  [23]	**Accelerometers**  [24]	**Flex Sensors**  [25]
Attachment Method	**Adhesive Strip**  [26]	**Glue**  [27]	**Fasteners**  [28]
Arrangement Method	**Inside the Part** 	**Back of Part** 	**Multi-Face** 

7. Concept Selection Process

Our morphological chart represented 27 possible designs, which we then had to narrow down. We did this by creating a diagram of potential design combinations and categorically narrowing them down. Below is a table representing the design eliminations we made considering various factors.

Table 7.1: Table of Morphological Design Eliminations

		Inside	Back	Multiface
Strain Gauges	Adhesive Strip			
	Glue			
	Fasteners			
Flex Sensors	Adhesive Strip			
	Glue			
	Fasteners			
Accelerometers	Adhesive Strip			
	Glue			
	Fasteners			

Feasibility Part Modifications Costliness Manufacturing Changes Practicality

i. Criteria for Eliminations

The criteria with which we eliminated designs were based on conversations with our sponsor and research into the compatibility of certain concepts. We considered the following factors:

- Feasibility: determining if it's possible to combine certain design concepts
  - Eliminations:
    - Fasteners with strain gauges - Strain gauges cannot be attached with fasteners due to the direct bond to the material that they need
    - Fasteners with flex sensors - Flex sensors are too thin to be reliably secured with fasteners.
- Need for part modifications: whether a design would require a modification of the bumper's design, which we decided was outside of our scope
  - Eliminations:
    - Fasteners with accelerometers - This would require making several holes in the part to attach fasteners for each accelerometer
- Costliness: Although cost is not a primary concern, certain designs may prove more costly without necessarily providing a worthwhile benefit

    - Eliminations:
        - Multiface placement of strain gauges - Measuring inward deflection with strain gauges mounted on top/bottom surfaces of part would require at least two rows to avoid placement on the neutral axis and may have needed closer arrangement.
        - Multiface placement of accelerometers - Accelerometers were the most expensive sensor considered, and placing them on multiple surfaces would not be useful as the relative motions they would provide would only be useful in crushing scenarios that are outside of our scope.
- Need for manufacturing changes: whether a design would require a change in Shape corp.'s manufacturing process at a costly step
    - Eliminations:
        - Placement of any sensor inside the part - This would require a change in Shape corp.'s roll forming manufacturing process, which is completed in a continuous series without interruption.
- Practicality: some designs may be possible but may have impracticalities due to combinations between certain concepts
    - Eliminations:
        - Adhesives with strain gauges - This would interrupt the direct bond to the material that a strain gauge needs to provide an accurate strain measurement.
        - Adhesives with accelerometers - These were deemed to be too weak to hold the weight of an accelerometer, due to the increased weight and the high accelerations that would be seen.
        - Multiface placement of flex sensors - Because the flex sensors only bend in one direction, they would have to be mounted on their sides which would prove challenging due to their thin and flexible form factor.

ii. Further Assessing Surviving Designs

After these eliminations, we were left with four designs that we were confident would be feasible for further evaluation. We then constructed a Pugh chart to assess these design concepts against criteria informed by our requirements and weighted by priority. The evaluation criteria are as follows:

- Measurement range: The range of displacements that this system would provide valid measurements for
- Sensitivity: How sensitive this measurement system would be to small changes in deflection
- Accuracy: How accurate the output of this system is predicted to be relative to actual deflection

- Operating temperature: Whether this system would be operational in the full temperature range set in our specifications
- Data complexity: How complex our algorithm would have to be in order to process the raw data of the system into useful deflection data
- Manufacturability: How easily this system could be manufactured using Shape corp.'s existing infrastructure
- Adhesion longevity: How reliable our system's attachment method is

Table 7.2: Pugh chart comparing the four selected designs against our design criteria. The asterisk on the second design's sensitivity rating is due to our lack of calibration curves for the flex sensors. The asterisk on the second design's data complexity rating is due to uncertainties about relative complexity between flex sensor- and strain gauge-based algorithms, as we have only seen strain used in previous research.

		Top 4 Concepts			
Criteria	**Weight**	**Flex Sensor Glue Back of Part**	**Strain Gauge Glue Back of Part**	**Flex Sensors Adhesive Strip Back of Part**	**Accelerometer Glue Back of Part**
Measurement Range	5	0	0	0	+1
Accuracy	5	0	0	0	-1
Sensitivity	5	0	+1*	0	-1
Operating Temperature	4	0	0	0	0
Data Complexity	3	0	+1*	0	-1
Manufacturability	2	0	-1	-1	0
Adhesion Longevity	2	0	0	-1	0
Cost	1	0	+1	0	-1
Total Score		**0**	**+7***	**-4**	**-9**

*Uncertainty about rating

Our highest-scoring design was strain gauges attached to the back of the part with glue, but with the caveat of uncertainties about its sensitivity and algorithmic complexity relative to the reference design. Due to these uncertainties, we have decided to pursue this design as well as the runner-up, which was flex sensors mounted with glue to the back of the part.

iii. Comparison to First Solution Concepts

Our team's initial solutions were envisioned during our research phase, when exploring different sensors that could fit our needs.

- Originally, we saw feasibility in an accelerometer-based system that would be attached inside the part.
- Both accelerometers and placement inside the part were carried relatively far into our design selection process.
    - Could be evidence of design fixation
    - More likely indicative of the relatively small solution space that we are exploring
- Our final selected designs incorporate neither of these aspects, however, as they were deemed not to be feasible or did not compare well to other potential designs.

8. Selected Concepts

This report section details our two chosen concepts, referred to as "alpha designs." Both designs feature a series of strain gauges or flex sensors aligned on the back face of the bumper structure, attached with the same mounting adhesive. The only distinction between the designs is the sensor spacing. Following initial testing on 03/12/2024, we will compare the results to select the final design.

i. Flex Sensor Concept

For the flex sensor concept we will be using 5 sensors to span an 8in segment of our bumper structure. There will be 0.25 in overlap between each sensor. The flex sensors are aligned such that there is a small amount of overlap that will prevent gaps in our data, while minimizing overlap that would increase the cost of our design without providing major benefits. After initial testing we will re-evaluate the sensor spacing to determine if more or less spacing will yield more accurate results. A schematic of the flex sensor placements can be seen in **Figure 8.1**.

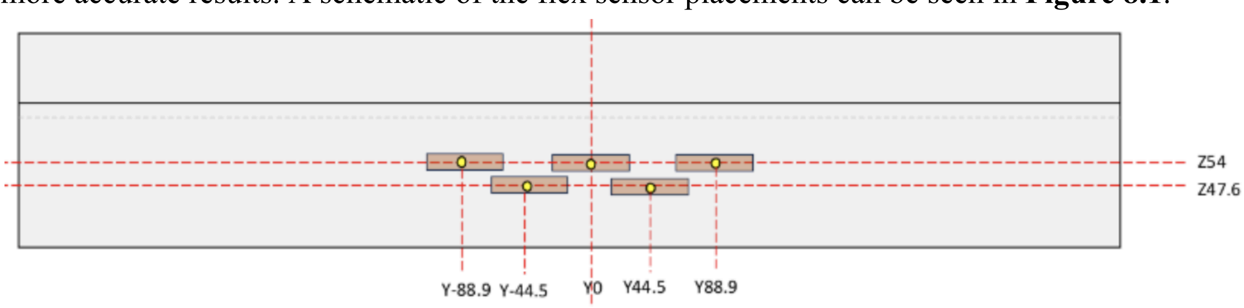


Figure 8.1: Flex Sensor Arrangement over 8 in Segment. (Dimensions in figure are in mm)

ii. Strain Gauge Concept

For the strain gauge concept we will be using 6 sensors to span an 8in segment of the bumper structure. We are limited by Shape Corp.'s testing equipment to 6 channels for our sensors, so we are using the maximum amount allotted by the equipment available. We are able to justify this through approximating the deformation shape of previous tests on the bumper. We can approximate the deformation shape as three piecewise linear lines with two discontinuities. A high level sketch of this can be seen in **Figure 8.2** below:

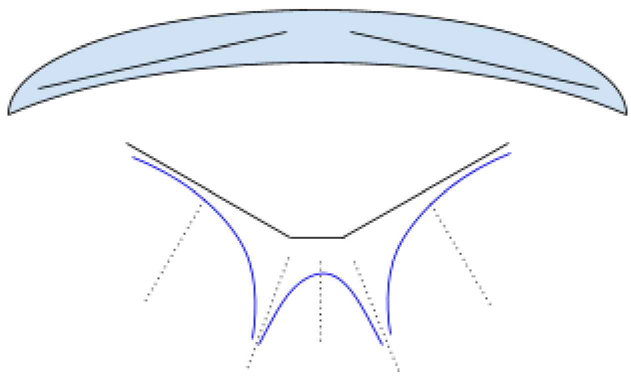


Figure 8.2: Deformation Shape and Possible Strain Curves.

The solid black lines show our approximated piecewise deformation with a possible set of strain curves between the discontinuities. Two points are required to make a line, so by having two sensors on each segment, and by having an understanding of the strain curve from the FEA, we can use a total of 6 strain gauges to depict the deformation across the entire 8 in span. From this analysis, we recommend to not use less than 6 strain gauges or else the overall deformation shape may not be accurately captured. The initial placement of the 6 strain gauges can be seen in **Figure 8.3** below.

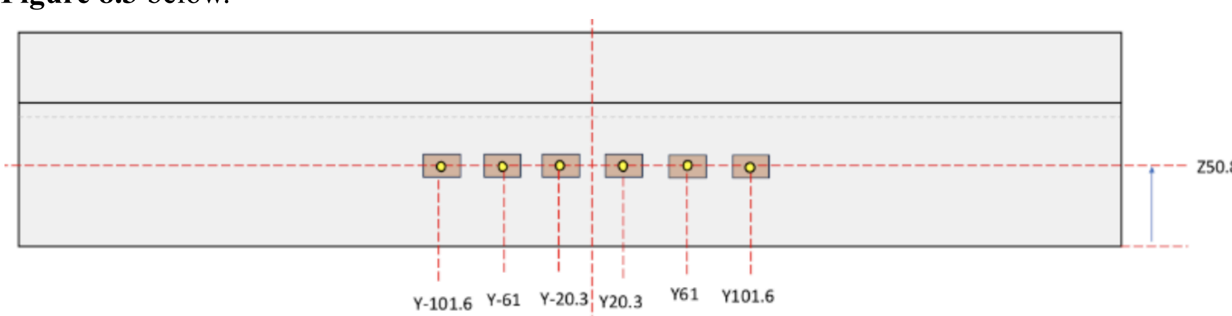


Figure 8.3: Strain Gauge Arrangement over 8 in Segment. (Dimensions in figure are in mm)

iii. DAQ Limitation to 6 Channels

In the scope of our project we are limited to 6 channels; however, once we have a proof of concept for the central 8 inches of the bumper, the sensing system will be expanded to the rest of the part. In light of this, we recommend using 9 strain gauges instead of the 6 allotted in our scope. This choice is based on the complexity of the strain curves presented in Figure 8.2 earlier, which is better approximated by a quadratic function with three points rather than a linear with two points. Therefore, with the absence of channel limitations, we suggest starting with 9 strain gauges and adjusting as necessary after initial testing.

iv. Sensor Placement Along the Height (Z-Direction)

In both alpha designs our sensors are centered along the z-direction, the height of the bumper. From the FEA data we determined two things:

- Stress, and thus strain, in the z-direction is small compared to the y-direction strain.
- The z-direction zero-stress line is along the middle of the bumper.

From these two insights we are comfortable in approximating the small z-direction stress to be zero by placing them along the zero-stress line across the middle of part. Thus, we recommend having both sensor systems to be centered across the z-direction.

iv. Parts for Selected Concepts Ordered

All parts for our two alpha designs have been ordered and shipped to Shape Corp.'s facility in Grand Haven, MI. The flex sensors purchased are Spectra Symbol Flex Sensors (part FLX-L-0055-123-ST) with a 55mm active length, and the strain gauges ordered are Omega Engineering strain gauges (part SGD-3S/120-LY11) with a 3mm grid length. 40 of each type of sensor were ordered to ensure we had enough sensors for multiple rounds of testing and calibration. Our bill of materials can be found in **Appendix C**.

v. Sponsor Influence

- Our sponsor recommended the adhesive that we will be using based on their experience with this adhesive for testing of other projects.
- During the research phase of our project, we shared information we had found about potential sensors, and our sponsor expressed an interest in flex sensors for our project as they had not seen them used for applications similar to our project.
    - We determined that carbon fiber sensors were not feasible for our project due to brittleness in the lower temperatures of our operating range.
- Our sponsor authorized testing on a limited section of the bumper structure, with the potential to scale up based on successful deflection recording.

9. Problem Analysis and Iteration

There are various relevant engineering fundamentals and scientific fields that will need to be involved to achieve project goals.

- *Signal Processing*: Understanding how to interpret sensor data and use the system to obtain accurate measurements is essential for meeting the requirement of measuring deflection. Initially investigating a broad and diverse background of different sensor types allowed us to narrow in on sensors that could best meet requirements and specifications [22]

- *Solid Mechanics*: Both plastic and elastic deformation are interconnected aspects of the structural response to external forces [20] [21]
    - Elastic Deformation: the reversible change in shape or size of a material in response to applied stress. It is a major contributor to the initial deflection before plastic deformation stage
    - Plastic Deformation: when a material undergoes permanent changes in shape or structure after being subjected to stress beyond its elastic limit
    - Beam Bending: The sensing system aims to accurately measure and analyze beam bending to quantify the extent of structural deformation. The knowledge of beam bending informs the optimal placement and integration of sensors on the structural component
- *Theoretical Models/Analysis*: Finite Element Analysis can be used to simulate crash scenarios and analyze deflection. Theoretical calculations can help estimate the forces based on measured deflection data
- *Empirical Testing*: Flex sensors and strain gauges will both be tested and compared to aid in our later design decisions. The option that best satisfies requirements and specifications will be further developed

To assess the feasibility of our chosen concept, we'll create small-scale proof-of-concept models for the sensing systems. Conducting deformation tests and comparing the results will determine if the system aligns with our engineering specifications. In case of inaccurate deflection data, we'll iterate on the design based on testing feedback and propose a new design for evaluation against the specifications.

10. Problem Domain Analysis and Reflection

This subsection discusses the engineering fundamentals needed to meet our quantified engineering specifications. It also identifies both resolved challenges and potential challenges that may arise, difficulties we may have due to limited knowledge and resources, the final "deliverable" that will be presented at the end of this semester, and the design drivers - the critical design parts and design decisions.

i. Final Deliverable

- Specified Sensor - give Shape Corp. specifications and supplier for what we determined to be the best sensor.
- Sensor Locations - give Shape Corp. a detailed engineering drawing of the exact placements and orientations of the sensors.

- Selected Adhesive - give Shape Corp. the exact adhesive we selected along with the specifications and rationale of chosen adhesive.
- Processing Algorithm - give Shape Corp. our processing system we develop to turn the data given by the sensors into useful deflection data that can depict the final shape of the deformed part.

Providing Shape Corp. with these four deliverables enables the installation of a sensing system on the bumper component. The system will undergo multiple tests in the upcoming semester, with the final design presented after thorough testing and validation.

ii. Design Drivers

- **Sensor Choice.** The first encountered design driver was the sensor choice, and it was critical that we choose the best sensors as it will depict the rest of our design. We systematically and narrowed down our sensor choices from eleven to three. From there we performed further preliminary analysis to get our top two sensor choices. After our initial testing that will occur on 03/12/2024 we will select the best sensor choice.
- **Sensor Spacing and Placement.** Optimizing sensor spacing is a crucial yet challenging aspect of design due to conflicting priorities. Maximizing accuracy requires minimizing sensor spacing, but this increases costs. Conversely, minimizing costs by increasing spacing compromises accuracy. The primary challenge lies in Shape Corp.'s limited DAQ channels (six), restricting our proof-of-concept to six sensors. To overcome this, we collaborate with Shape Corp.'s technician, gather sensor specs, and employ FEA for optimal sensor placements to ensure accurate data.

While acknowledging the challenges posed by these design drivers, we are confident in our team's ability to address and overcome them. We extensively researched and consulted faculty specialists to ensure our selected sensors meet the requirements. Additionally, for sensor spacing and placement, we leverage the expertise of Shape Corp.'s technicians and their testing facility to determine the optimal configuration.

iii. Challenges

- Potential challenges that may arise throughout this project can be seen in Table 10.1, pg. 25. Included in the table is the challenge, the reasoning behind the challenge, and our proactive approach to reduce the effects of these possible setbacks.

Table 10.1: Identification, rationale, and approach for each potential future challenges

Potential Challenge	Reasoning	Proactive Approach
Sensor Availability	We are limited to available sensors already in the market, and we don't have enough time to make our own sensor for specified requirements.	We will devote a significant amount of time early on to research and gather information on dozens of relevant sensors. We will perform a series of thorough comparisons to narrow down our top sensor choices. Also, we will meet with faculty that have expertise in sensors.
Product Shipping	We have limited control over the shipping time and in-stock sensors. 40 of each sensor type were ordered on Feb 20.	We will order the sensors as early as possible, tentatively before Feb 22.
Time Conflicts for Testing	Testing will be done at Shape Corp.'s facility in Grand Haven, MI during business hours. We will have to coordinate with Shape Corp. to reserve time in their facility, and miss classes to perform testing.	We plan to have our prototype built early in our project timeline to allow for flexibility in the testing period. The sensors have been ordered, the bumper has arrived, and we have scheduled a test with Shape Corp.'s technician on March 12.

- Also, our sensor originally needed to endure 365 °F for one hour as a requirement. After discussing our concerns with the sponsor we reached an agreement. Due to Shape Corp.'s manufacturing flexibility, they can now incorporate the sensors in conditions more similar to the operating ones.
    - Consequently, our sensor no longer has to withstand 365 °F for one hour, though Shape Corp. still expresses a preference for it.

iv. Information Gaps

- Shape Corp. doesn't provide a sensor supplier database for this project, but they prefer sensors from reputable suppliers.
    - Our team will independently find suppliers once a sensor is selected.
    - To address the information gap, we'll contact various suppliers and consult UMich faculty with sensor expertise for input.
- We have a need for an advanced testing facility and skilled operators for our project.
    - Shape Corp will provide specialized equipment and technical support, leveraging their expertise in operating the required testing equipment.

Both of these prior information gaps no longer exist as we have selected our sensors, and we have coordinated our first test date with Shape Corp.' skilled technicians at their testing facility.

11. Engineering Analysis (Before Testing at Shape Corp.)

We have used and are planning to use a variety of engineering analysis methods to develop, evaluate, refine, and optimize our design with respect to the requirements and specifications.

i. Research and Specification Analysis

We conducted thorough research on current methods of using sensors to measure deformation of structural components. A third-party group had success measuring deformation of an airplane wing using very small, accurate strain gauges [30]. This paper and ones like it gave us confidence that using strain gauges could have a successful outcome for measuring deformation. We also researched a vast array of sensors to ensure we chose sensors that best met our specifications. These included strain gauges, flex sensors, accelerometers, pressure sensors, LVDTs, and various others. After identifying potential sensors, we examined their specification sheets to ensure the sensors would meet our requirements and specifications. Potential sensing systems were compared by the following criteria: measurement range, sensitivity, operating temperature, data complexity, manufacturability, adhesion longevity, and cost.

ii. FEA and Prior Experimental Evidence

Shape Corp. provided us with FEA screenshots of the bumper deforming under an applied load of 50.8 kN in the center of the part. These screenshots are given below as **Figures 11.1-3**. From these images, we were able to analyze:

- the overall deflection (displacement) of the beam
- the strain on various portions across the beam
- the stress distribution across the beam

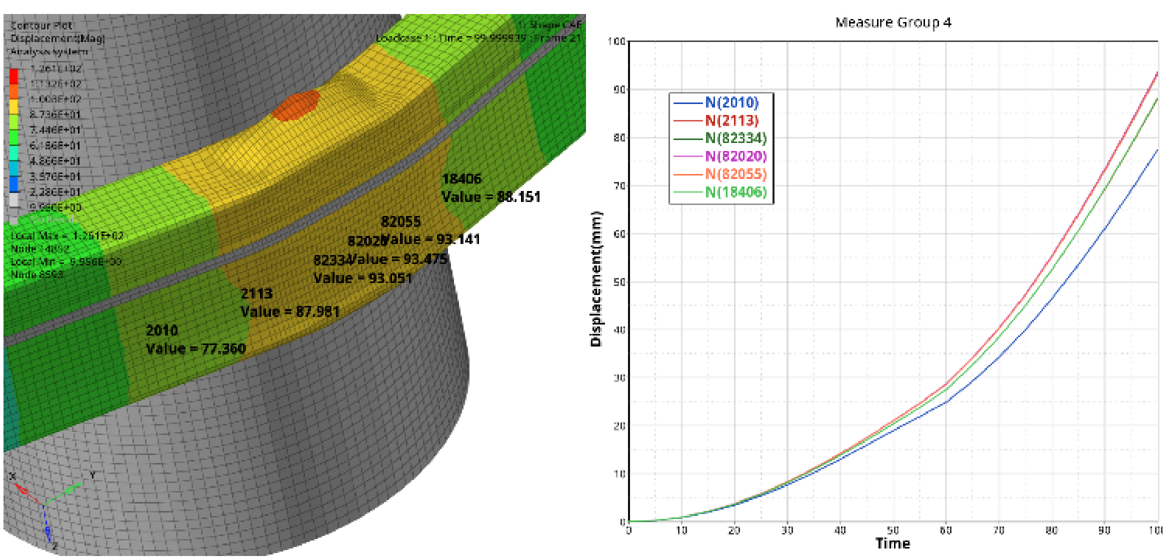


Figure 11.1: The FEA deflection (displacement) screenshot [1] provided to our team by Shape Corp.: 50.8 kN applied force. As expected, the part experiences the most displacement in the center region where the force is applied.

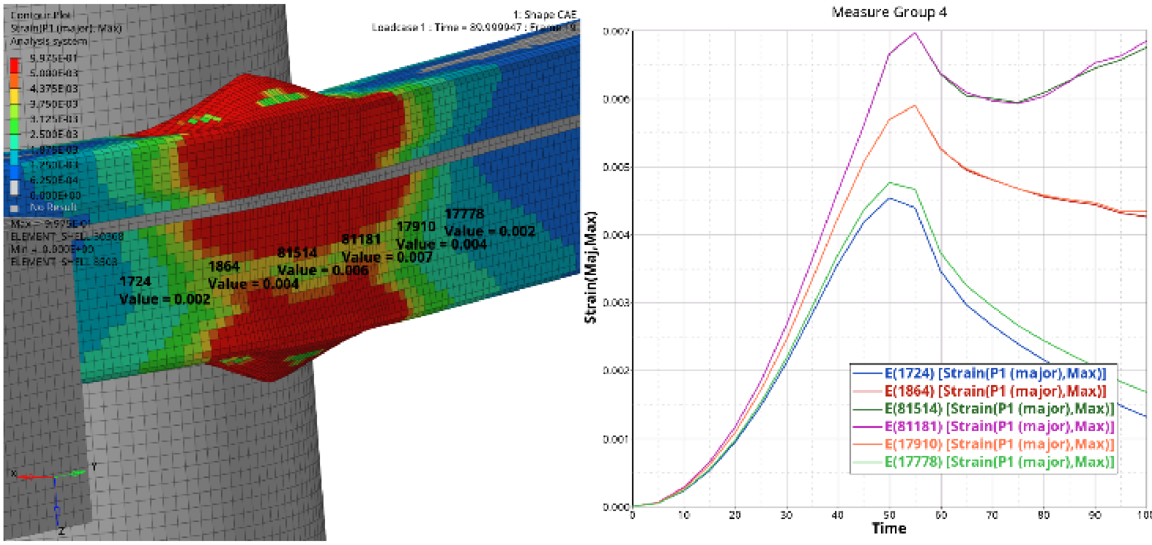


Figure 11.2: The FEA strain screenshot [1] provided to our team by Shape Corp.: 50.8 kN applied force.

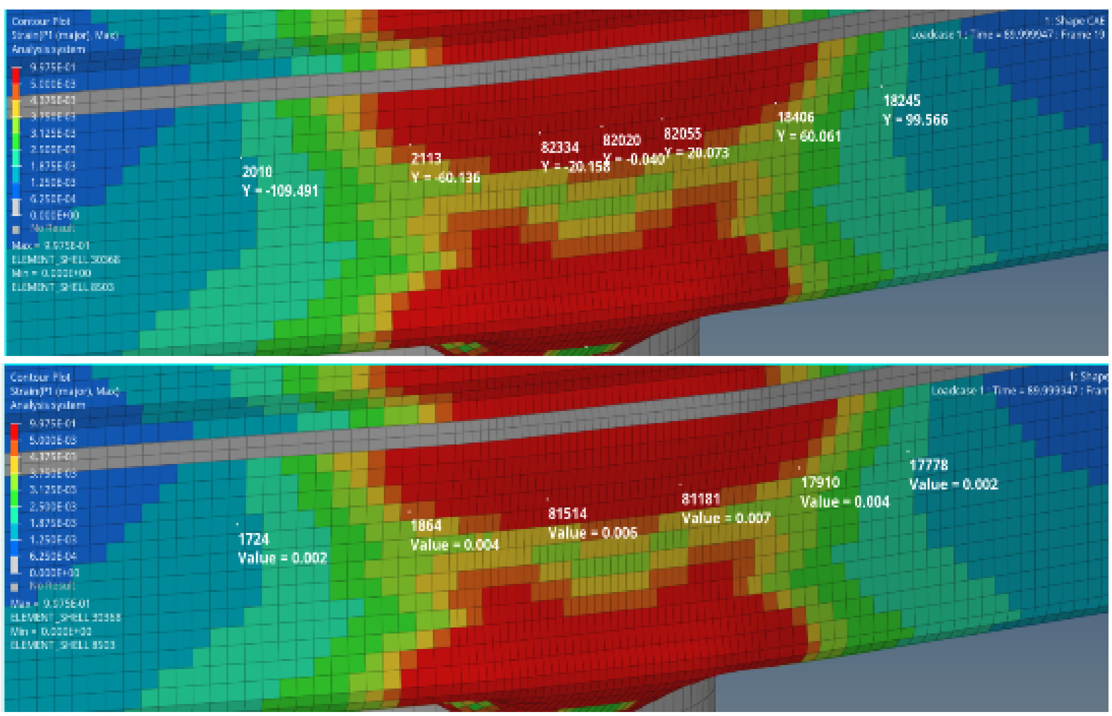


Figure 11.3: The FEA stress distribution screenshot [1] provided to our team by Shape Corp.: 50.8 N applied force. Notably, the centerline of the beam has a low area of stress.

From analyzing these images, we were able to have a better idea of where to place sensors to interpret the data to calculate deflection:

- Areas of high stress are correlated with high strain and deflection (displacement).

- The strain is minimized along the centerline of the part
    - Placing sensors here will mean they will experience minimal z-direction strain (strain in the vertical direction as viewed in the figures above) as compared to being on the top or bottom edge of the part

iii. Analysis to Ensure Flex Sensor Survives Deformation and Loading

A variety of approaches were taken prior to testing to ensure flex sensors would be able to survive the deformation. The flex sensor specification sheet states the sensor can bend up to 180° [31]. We also were able to find demonstration videos online of people bending a flex sensor 180°, and they survived and recorded data throughout the entire bend [31].

We analyzed the material properties and geometry of flex sensors to estimate their maximum elongation and withstandable force. A diagram of the flex sensor can be seen in **Figure 11.4**.

- Determined the cross-sectional area of the flex sensor [31]

$$\text{Cross Sectional Area} = \text{Thickness x Width}$$
$$= 0.13\text{mm x } 6.35\text{mm}$$
$$= 0.8255\text{mm}^2$$

Figure 11.4: The cross sectional area of the flex sensor is approximately 0.8255mm^2.

- Identified material of flex sensor to be polyimide from flex sensor spec sheet [31]
    - Young's modulus is a measure of the stiffness or rigidity of a material
    - Tensile strength is a measure of the maximum stress a material can withstand without breaking or fracturing

Table 11.1: Relevant material properties of polyimide [32]

Property	Value
Young's modulus	2.5 GPa
Poisson ratio	0.34 @ 23°C
Tensile strength	231 MPa @ 23°C 139 MPa @ 200°C
Melting Point	Does not melt, Decomposes at 520°C

- **Determine maximum elongation:**
  - Obtain the stress-strain curve for the material
    - Assume that the material behaves linearly elastic up to its yield point
    - Use Young's modulus to determine the slope of the linear elastic region of the stress-strain curve
    - Maximum stress point is the tensile strength
  - Calculate the strain corresponding to the tensile strength
    - Max strain = 231 MPa / 2.5 GPa = 0.0924 = 9.24%

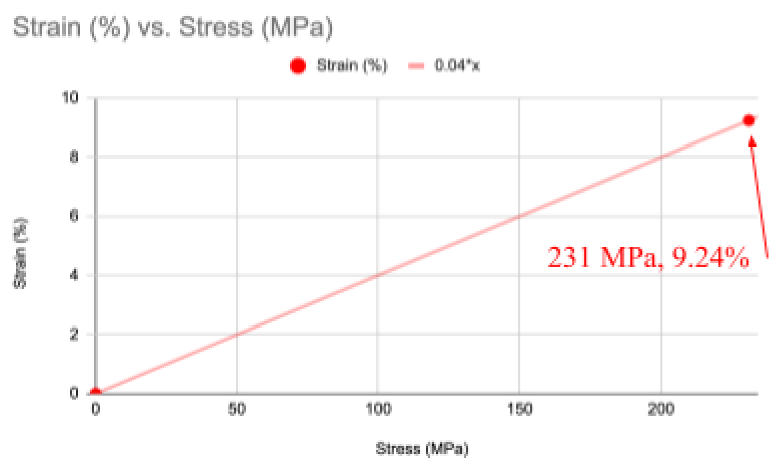


Figure 11.5: This simplified stress-strain curve provides a basic visualization of the material's behavior up to its yield point, based on the given Young's modulus and tensile strengths.

  - This maximum elongation of the flex sensor is less than what a flex sensor will experience for our test. We verified this by comparing deformed and undeformed parts.

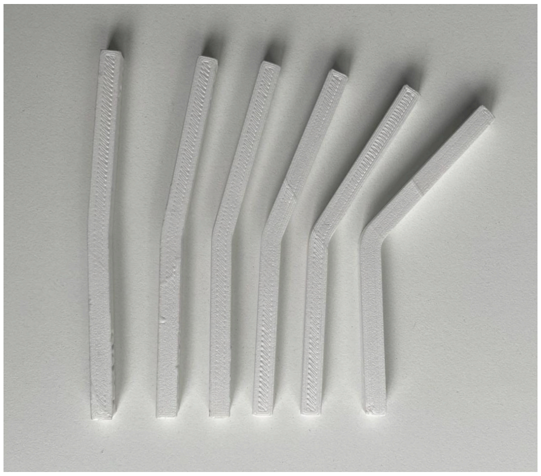
- **Determine max force that flex sensor can experience:**
  - Using the tensile strength of polyimide and the cross sectional area of the sensor, we can estimate the flex sensor is able to withstand 190 N before it will break or fracture: 231 MPa (N/mm^2) x $0.8255mm^2$ = 191 N.

iv. Calibration of Flex Sensors

Because there were no publicly available calibration curves for the flex sensors, we had to perform our own testing to determine the relationship between bending and resistance change of the flex sensors. To do this, we:

- 3D printed bends of different angles
- Placed flex sensors across these bends
- Recorded their change in resistance relative to the flat sensor resistance

The 3D printed bends used as well as the results of this calibration are shown below in **Figures 11.6-11.7**.



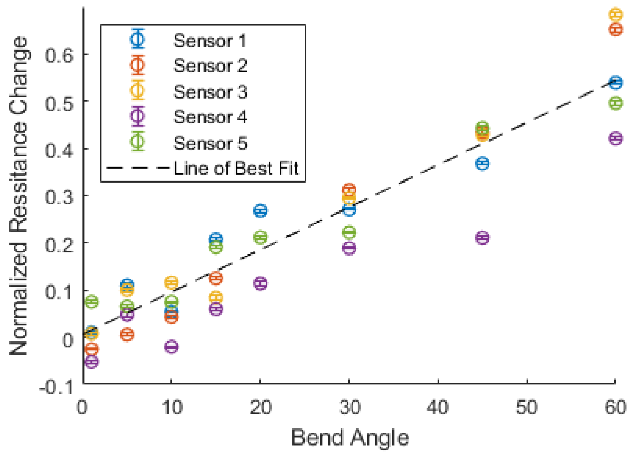


Figure 11.6: A sample set of the implements used to bend the Flex Sensors at specific angles. The angles shown here at 5, 10, 15, 20, 30, and 45 degrees, with a 1 cm radius of curvature.

Figure 11.7: A plot of the normalized resistance changes of the flex sensors when bent at several angles of 1 cm radius. Multiple sensors were used to quantify the resistance variance between sensors. Precision errors are shown but are small relative to the values.

From the results in **Figure 11.7**, we can see that not only is there a high variance in the resistance changes between different sensors, there is also a highly variable relationship between bend angle and resistance for each of the individual sensors tested. These results provide us with little confidence that flex sensor readings can be accurately and precisely attributed to an angle of bending. Despite this, our sponsor encouraged us to test a physical prototype to fully understand how these flex sensors will behave during a test.

v. Engineering Analysis for Each Specification

Specification 1: Sensors should measure the deflection of the bumper structure up to 100 mm in 1 mm steps, and with an accuracy of 25% to true deflection.

- Analysis Plan:
    - Research and Specification Sheets Analysis: Conduct exhaustive research on the available sensors and carefully examine their specification sheets to verify that they are capable of measuring deflection up to 100 mm with precision increments of 1 mm.
    - Generating Algorithm Test Inputs: For the flex sensor-based and the strain gauge-based algorithms, test inputs were generated using representative beam shape functions and FEA data (provided by Shape Corp.), respectively. The output of the algorithms were compared to the expected deflection values to ensure accuracy.
- Justification:
    - Utilizing research and specification sheets analysis is a cost-effective and time-efficient approach to gain preliminary insights into sensor capabilities, providing a moderate level of confidence in meeting the specification.

    - Generating sample inputs allow testing of an algorithm without needing physical data, and provide a reasonable way to approximate the algorithm's functionality and accuracy in a physical testing environment.
- Limitations:
    - While specification sheets may provide information on sensor accuracy, they may not fully account for the integration of sensors into the overall sensing system, including algorithm performance.
    - The replication of the algorithm's performance can only be as good as the sample data, which must be carefully constructed in order to approximate the expected data as closely as possible.
- Key Results:
    - Using the flex sensor algorithm, errors larger than 25% were seen only with displacements smaller than 12 mm. No errors above 25% were seen at large displacements, which generally had errors of less than 10%. The flex-sensor algorithm deformation results were found to be within 4.1% error to the virtual deformation scenario using sample data representing 100 mm of displacement. A representative result from a sample deformation scenario can be found in Figure D.2, Appendix D.
    - The strain-gauge based algorithm had a maximum error of 27% relative to the FEA data, but this was at a small displacement of 8 mm. No errors above 25% were seen at larger amplitudes of displacement. A comparison between the algorithm-predicted displacements and actual displacements from the FEA data can be found in Figure D.1, Appendix D.

Specification 2: Survive a load range up to 50kN.

- Analysis Plan:
    - FEA Analysis of Parts: Shape corp. has provided us with FEA data which gives us an estimate of the strains seen during their tests that involve loads up to 50 kN. These strains will allow us to verify that our sensors can survive the loads seen during testing.
- Justification:
    - Our sensors will not have to experience 50 kN of force directly, but will instead need to be able to measure the bumper component's deformation response to the loads applied. Thus, our sensors will only need to survive the strains experienced by the component in this load scenario.
- Limitations:
    - The strain response of parts will change based on the part being tested, for instance a thinner part would experience more strain than a thicker part under the same applied load.

- Key Results:
    - The FEA data indicates our expected strains will be smaller than the maximum strain measurable by our strain gauges, and will be survivable by the flex sensors.

Specification 3: Provide requested deflection data within 4 minutes of tested impact.

- Analysis Plan:
    - Running the Algorithm Using Test Inputs: The algorithms will be run using sample inputs that replicate the sensor readings we expect to receive, and the processing times of the algorithms will be recorded.
    - Performing Time Complexity Analysis on the Algorithm: Analyzing the algorithm's time complexity will determine how processing time scales with additional sensors, ensuring adaptability to future design modifications.
- Justification:
    - Processing times for algorithms are generally consistent when run multiple times. We expect our timing of the processing time to be relatively accurate for future runs with real data.
    - By considering time complexity alongside current processing time, we can reliably estimate how processing time will scale with increased inputs for our algorithm.
- Limitations:
    - Sample inputs will likely differ from actual sensor readings, which could slightly change the processing times of the algorithms.
    - The processing time may change depending on the processing power of the computer that runs it. While the integration of our system and algorithm into the vehicle computer is outside of our scope, it is still worthwhile to consider that processing time may be different than the times of the computers available to us.
- Key Results:
    - Processing time for our current algorithms are minimal, and are each less than 10 seconds.
    - The current strain gauge algorithm has worst-case $O(n^3)$ time complexity for solving linear regression, which would scale unfavorably, but the small processing time that we see for our design leaves room for a sizable increase in the number of sensors.
    - The current flex sensor algorithm has worst-case $O(n^2)$ time complexity, but would likely see performance closer to $O(n)$, which would scale somewhat favorably with an increased number of sensors.

Specification 4: Sensors should operate between -40 and 140°F.

- Analysis Plan:
  - We performed preliminary research of various sensors before selecting the flex sensors and strain gauges we are using for this project based on their product specification sheets, which state that they will operate under the required temperature conditions.
- Justification:
  - Product specification sheets contain information regarding the size, construction and performance of a product according to the manufacturer of the component. These specifications show that the sensors we chose will operate in the temperature range required for our system.
- Limitations:
  - Although product specification sheets should be accurate, actual testing would better ensure the system performs in the specified range of operating conditions
- Key Results:
  - The flex sensors have operating temperatures between -31ºF and 176ºF and the strain gauges have operating temperature ranges of -103ºF through 392ºF according to the specification sheets.
    - Although the flex sensor's operating range is limited to -31ºF, Shape Corp. gave our team approval to test the flex sensors because temperatures will not frequently reach -40ºF and our sponsors are interested in how the flex sensors function for this application.

Specification 5: Tools needed for installation be limited to those provided with purchase of sensor and those available in University of Michigan machine shop. Use ≤1 type of adhesive.

- Analysis Plan:
  - When exploring sensor types and adhesion methods, we aimed for ease of installation. We opted for the Vishay M-Bond 200 Strain Gage Adhesive kit, suggested by our sponsor for its quick and secure attachment capabilities, streamlining system integration into production.
- Justification:
  - The adhesive kit contains two fluids: one acts as a catalyst and is not adhesive on its own, ensuring compliance with the requirement of using ≤1 adhesion type. Other necessary installation tools, such as a degreaser, sandpaper, calipers, tape measure, soldering iron and wire, and scotch tape, are available in the University of Michigan MechE Machine Shop or the mechatronics lab.
- Limitations:
  - We are not certain of every tool that can be found in the machine shop and tools are used by multiple teams and individuals throughout the day, so gaining access

to all of these tools to install our sensors could prove difficult if we need to conduct further testing and set up another bumper structure for testing.

- Key Results:
    - The sensors will be attached using an adhesive and catalyst duo from a strain gauge adhesive kit and can be installed using tools that can be found in the machine shop at the University of Michigan.

Specification 6: Take up less than 15% of surface area available on the specified part. System should protrude <25 mm from the surface of the part.

- Analysis Plan:
    - Sensors were chosen to meet project specifications, utilizing data from product spec sheets. Flex sensor and strain gauge dimensions were sourced from manufacturer websites. Initial assessments were made to determine the number of sensors required to cover <15% of the bumper's surface area. Sensor depth was considered to prevent interference with existing vehicle components.
- Justification:
    - The product specification sheets provide dimensions for the sensors that were considered to ensure our system adequately satisfies our stakeholder specifications.
- Limitations:
    - Our analysis relied solely on the information provided in the product specification sheet, as we did not have physical access to the products for measurements.
- Key Results:
    - The surface area of 6 strain gauges or 5 flex sensors is within the limits of space allotted. A single strain gauge has a surface area of 5.1mm^2, so six strain gauges would take up 30.6mm^2. There is a total surface area of 19,304mm^2 available on the bumper, so the strain gauges take up approximately 0.2% of the available surface area. Each flex sensor has a surface area of approximately 556.5mm^2[31], so five flex sensors would take up 2,782.3mm^2. The flex sensors would take up approximately 14.4% of the available space in the middle portion we are considering.

12. Build Design/Final Design Description

i. Build Designs (2)

As of 03/28/2024, our project features two build designs, initially referred to as "alpha designs." These designs underwent minor adjustments during the transition to build designs, but the overall structure remained unchanged. The strain gauge build design incorporates 6 Omega Engineering strain gauges (part SGD-3S/120-LY11) affixed to a Shape Corp. bumper at y locations (-101.6, -61, -20.3, 20.3, 61, 101.6 (mm)), z location 50.8 mm, and using M-Bond 200 adhesive.

Similarly, the flex sensor build design integrates 5 Spectra Symbol Flex Sensors (part FLX-L-0055-123-ST) mounted onto a bumper at y locations (-88.9, -44.5, 0, 44.5, 88.9 (mm)), z locations alternated between 47.6 and 54 mm, and using the same adhesive. For detailed components, please refer to Appendix C in our bill of materials.

The two build designs were both tested at Shape Corp.'s testing facility in Grand Haven, MI on 03/12/24. The strain gauge build design after testing is shown below in **Figure 12.1**, and the flex sensor build design prior to testing is shown below in **Figure 12.2**.

Figure 12.1: Strain Gauge Build Design Post Testing. This picture showcases the 6 strain gauges each adhered to their specified locations, and proves that the sensor build design stays intact throughout testing.

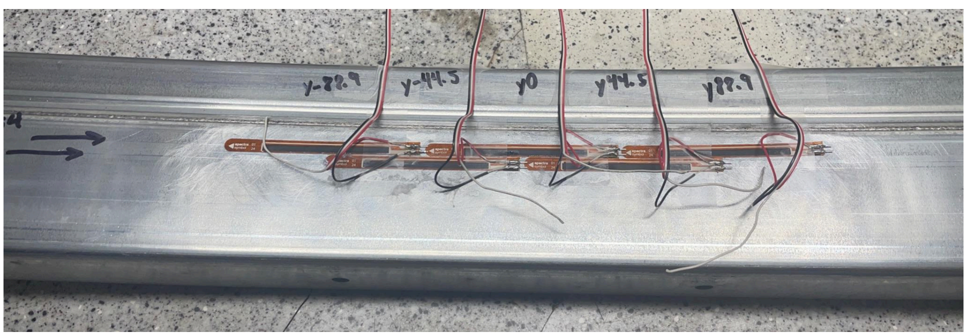


Figure 12.2: Flex Sensor Build Design After Testing. This picture showcases the 5 flex sensors each adhered to their specified locations.

ii. Algorithm Designs (2)

Flex Sensor Algorithm: This algorithm is based on recreating the shape of the post-deformation bumper by creating a function representing the original shape of the component and estimating the location and degree of bending experienced during the test. A flowchart of this algorithm can be found in **Figure 12.3** on pg. 36:

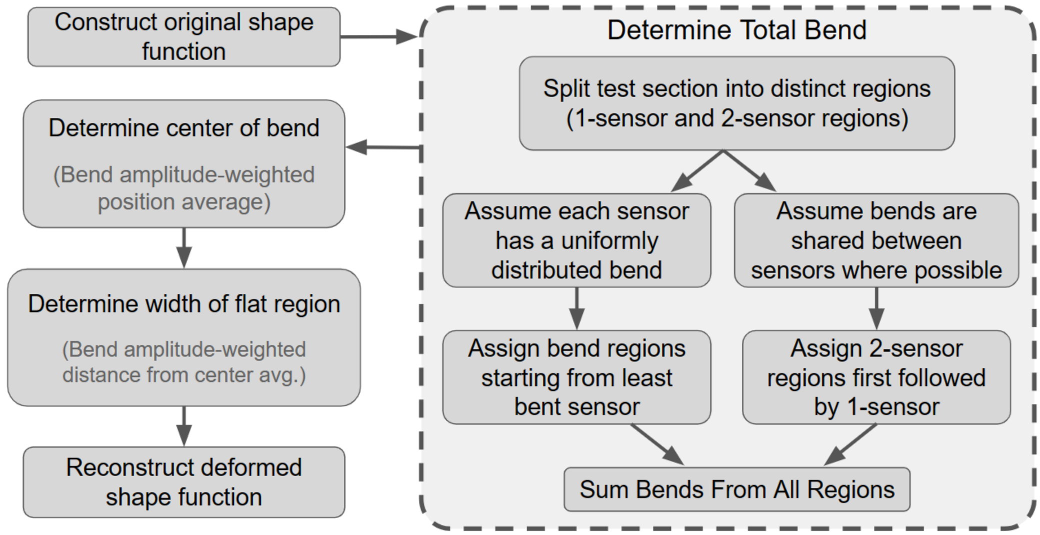


Figure 12.3: Flowchart detailing the steps of the flex sensor-based deflection algorithm

- Construct Original Shape Function: We have constructed a function representing the original shape of the component based on measurements of the bumper provided by Shape Corp. At this time the function assumes a constant radius of curvature across the component.
- Determining Total Bend: This step involves splitting the region of interest into several regions; regions with only one sensor, and regions where sensors overlap. Overall bends across each sensor are then divided into each section.
  - Uniform bends: This bend assignment algorithm assumes each sensor has a uniform bend across its length, and assigns a bend to each region depending on its size. This algorithm starts on the outermost sensors and works progressively inwards, ending with the center sensor. This algorithm may provide an overestimate of total bending.
  - Shared bends: This bend assignment algorithm assigns in the overlapping sensor region the maximum amount of bend that could be shared between two sensors, starting from the outer sensors and working inward toward the center. This algorithm would provide a minimum estimate of total bending. Initial analysis using test inputs showed that this method led to more accurate results.
- Determining the Center of Bending: This step involves determining the location along the part where the center of the bend is located. It is based on a bend amplitude-weighted average of position.
- Determining the Width of the Flat Region: With the observation that a component bend exhibits a central flat region on the back of a part bordered by two bends, this step determines the width of this region based on the bend amplitude-weighted distance from the bend center from the previous step.
- Reconstruction of Deformed Shape Function: This step adjusts the original shape function by incorporating the bend center, flat region width, and total bending. It creates a

flat region with bends on both sides, each representing half of the total calculated bend. The final displacement value is determined by finding the maximum deviation between the original and post-deformation shape functions.

Strain Gauge Algorithm: This algorithm is based on creating polynomial fits of the strain function across the back of the part, and relating the parameters of this fit to the measured deflection with an empirical model using linear regression. A flowchart of the steps of this algorithm can be found in **Figure 12.4** below:

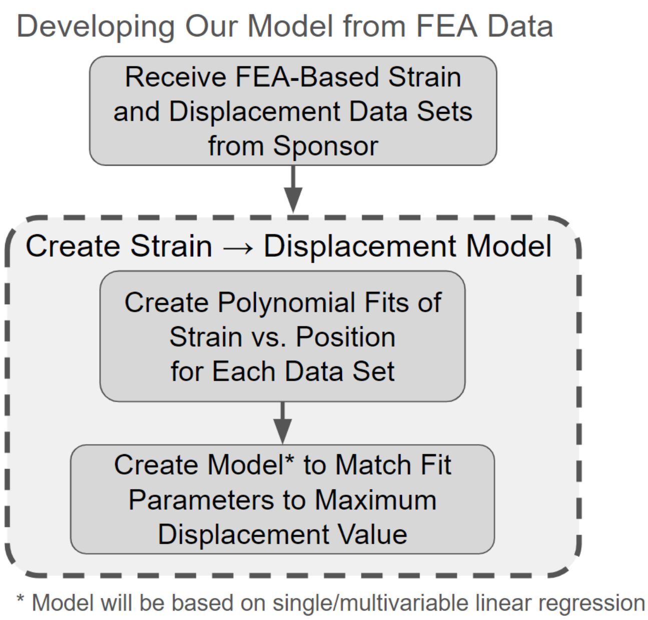


Figure 12.4: Flowchart detailing the steps of the strain gauge-based deflection algorithm

- Developing our Model from FEA Data: Using the FEA data of a similar part bending scenario provided to us by Shape corp., we will develop a model of how polynomial fit parameters relate to the overall deflection observed.
    - Creating Polynomial Fits of Strain v. Position Data: Based on the strain data seen at different locations across the FEA simulated part, a polynomial fit is constructed using built-in functions in matlab.
    - Creating Strain-Displacement Model: Based on several sets of polynomial fit parameters and the corresponding displacement observed in each case, an empirical model will be constructed based on multivariable linear regression.
- Processing Strain Gauge Data: Using the readings collected from physical testing or in a real-world scenario, a polynomial fit would be created to the strain-position data, then the fit parameters would be used as inputs to our strain-displacement model, outputting our final displacement value.

iii. Final Design

After performing physical testing of both build designs, we determined that our strain gauge design is most viable. We ruled out the flex sensor-based design for several reasons:

- The calibration of flex sensors showed a highly variable relationship between bend angle and resistance change, which we deemed too inaccurate for our application. The methodology and results of this calibration can be found in **Section 11.iv**.
- The data collected during our flex sensor build design tests showed unreasonably high changes in resistance, up to more than 10 times the flat resistance, representing an unreasonable degree of bending. We attribute this to the combination of bending and axial strain that the sensors experienced, which would require much more analysis and a more complex algorithm that we did not have time to explore over the course of this project. An example result from this testing is shown below in **Figure 12.5**.

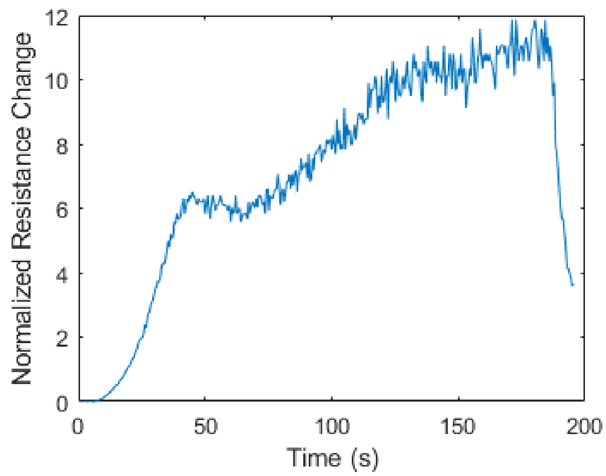


Figure 12.5: A sample sensor output from the test of our flex sensor-based design. The resistance rises to nearly 12 times the base resistance, which is a nonsensical value compared to the small resistances we expected for this test. For instance, from our calibration we would expect a normalized resistance change of 0.5 for a 60 degree bend, which is several times higher than the bend angle seen.

Our final design consisted of 6 Omega Engineering strain gauges (part SGD-3S/120-LY11) affixed to a Shape Corp. bumper at y locations (-101.6, -61, -20.3, 20.3, 61, 101.6 (mm)) (or -4.0, -2.4, -0.8, 0.8, 2.4, 4.0 (in)), z location 50.8 mm (2 in), and attached using M-Bond 200 adhesive. A diagram of this placement is shown below in **Figure 12.6, pg 39.**

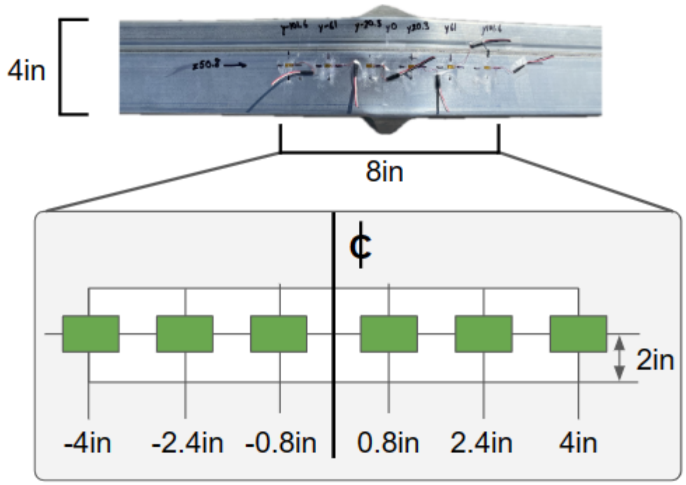


Figure 12.6: Diagram of strain gauge placement on the back of the part.

Our algorithm was data-driven, and used polynomial fits of strain readings to reconstruct the strain function across the back of the part. The coefficients of these polynomial fits were then related to the displacement using a linear regression model. Although we originally planned to use FEA data to construct this model, we found that this provided less accurate results when compared to the model constructed using test data. This is discussed further in **Section 13.i**, and shown in **Figure 13.2**, **pg. 41**. Thus, we used test data to construct the final model, the results of which can be seen below in **Figure 12.7**.

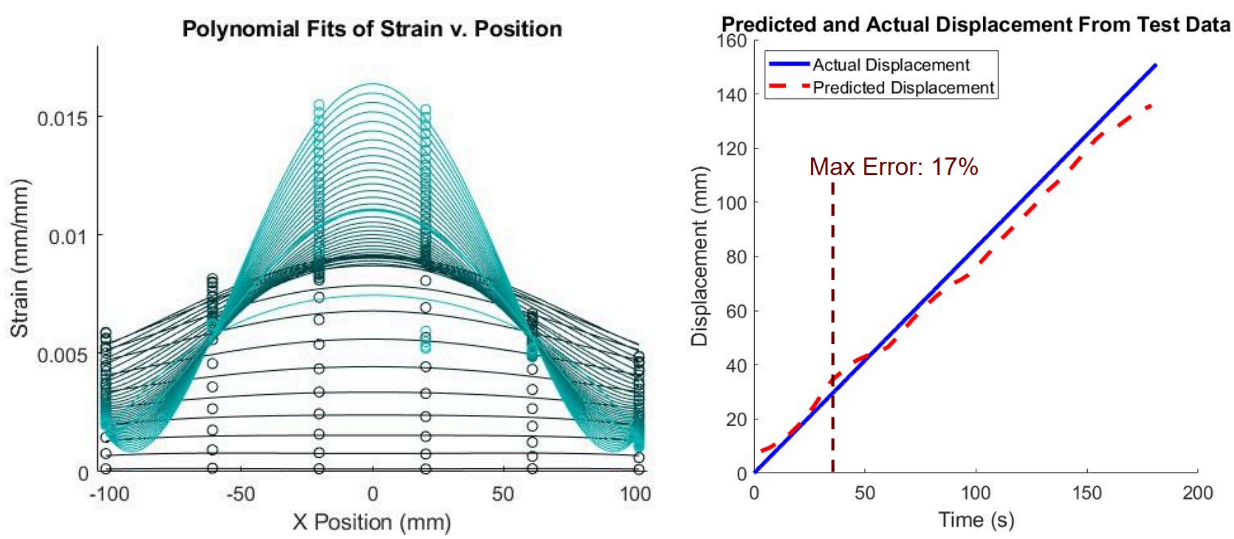


Figure 12.7: Results of the strain-based algorithm for our physical testing. On the left is a set of polynomial fits to the strain data of the test, the coefficients were used to predict displacement based on our linear regression model. The output of this model is shown on the right, where we see a close relationship between predicted and actual displacement. The maximum error was 17%, at an actual displacement of 29.5 mm.

13. Verification Plans

On Tuesday, March 12th, 2024, our team commenced testing our build designs at Shape Corp.'s Grand Haven facility. During the initial test, we observed that the soldered-lead strain gauges, which were our original choice, failed due to solder connection failures while data acquisition was ongoing. Subsequently, in our second round of testing, we utilized strain gauges with identical specifications sourced from the same supplier, but with ribbon leads instead. We proceeded to prepare and install the selected sensor systems using the adhesion method endorsed by our sponsor, along with their recommended adhesive and catalyst.

The installation process of our strain gauges and flex sensors, as outlined by **Figure 13.1** below, involved several steps. First, we degreased the part using CSM-3 degreaser and a cotton round to ensure a clean base (1.). Next, we marked the sensor locations with a caliper and measuring tape, followed by roughening the surface with sandpaper (2.). After degreasing again to remove any surface residue and labeling the sensor locations (3.), we aligned the sensors using folded-over scotch tape to secure them in place (4.). Then, we applied the adhesive and catalyst to the part along the fold of the tape and smoothed down the sensors (5.), applying light pressure for one minute to secure the adhesion (6.). For the flex sensors, which have large ribbon leads, we soldered 6 ft long wires for connection to the DAQ system for data acquisition (7.).

Figure 13.1: Installation process of strain gauges and flex sensors followed on Tuesday, March 12th, 2024.

i. Verification Plan for Each Specification

Specification 1: Sensors should measure the deflection of the bumper structure up to 100 mm in 1 mm steps, and with an accuracy of 25% to true deflection.

- Analysis Performed:
  - We performed empirical testing to validate the sensing system's ability to measure deflection accurately within the specified range.

■ Subjected the sensors to controlled deformation scenarios and compared the system's measured deflection with the actual deflection to verify accuracy.

- Key Results:
  - We compared the measured deflection from our model and the prescribed deflection from the test. The accuracy is within 17% at all deflection readings.
  - We found that the model relating polynomial fit parameters to displacement in the strain gauge-based algorithm was less accurate when constructed with the FEA data as opposed to the physical test data we collected. A comparison of the displacement results from each model is shown below in **Figure 13.2**.
    - ■ This may be due to the disagreement between the FEA data and the test data when comparing the strain readings at the same displacement. These discrepancies in strain can be seen in **Figure 13.3.**
- Justification:
  - Empirical testing provided concrete validation by directly assessing sensor performance in real-world conditions, allowing for a more accurate evaluation of whether the sensors and algorithm can meet the specified deflection measurement requirements.
- Limitations:
  - Empirical testing may not fully replicate all potential operating conditions that could occur in a complex, real-world deformation.

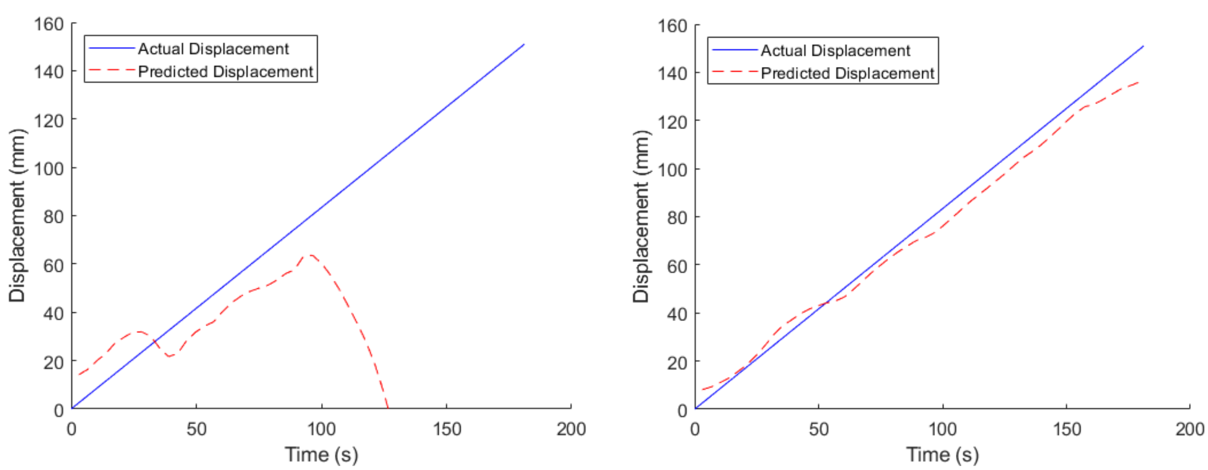


Figure 13.2: Actual displacements compared to displacements predicted with our strain-gauge based algorithm when constructed using FEA data (left) and test data (right). We can see that while the FEA data-constructed model's displacement shows a loose fit before completely deviating from the actual data, the test data-constructed model shows a close fit throughout the run of the test.

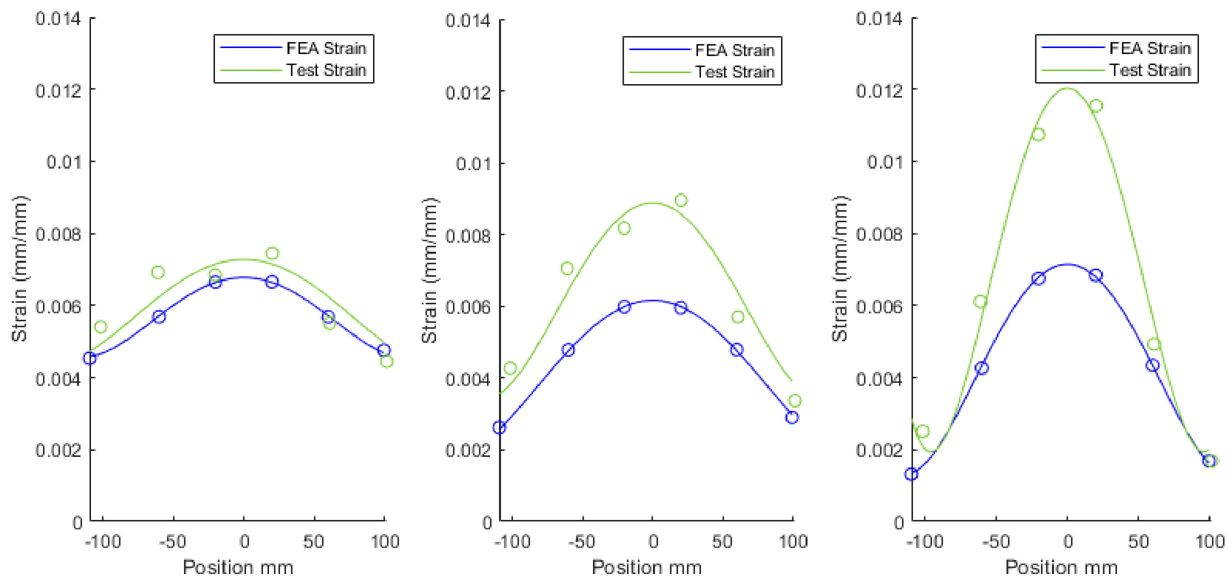


Figure 13.3: Values and polynomial fits of FEA strain data (green) and test strain data (blue) at bumper displacements of 25 mm (left), 50 mm (center), and 100 mm (right). We can see that while the FEA and test data show a relatively close agreement at lower displacements, the discrepancies become larger at greater displacements.

Specification 2: Survive a load range up to 50 kN.

- Analysis Performed:
  - We prescribed a displacement of 0.5 mm every second, up to 150 mm, to the bumper with our sensing system installed, and we measured the force applied alongside the respective sensor output.
- Key Results
  - The soldering connections were too thin and became disconnected during the initial round of testing with strain gauges.
    - The DAQ did not initially obtain sensor data.
    - This failure in the robustness of our sensing system led us to swap the strain gauges out for ones of the exact same spec but with pre-installed wires.
  - In performing our testing, plastic deformation occurred after 35 kN of force, and the sensors saw a decrease in strain as a result of the front of the bumper buckling and dispersing strain from the sensor locations. If desired, Shape Corp. can perform a different test to verify this specification.
- Justification:
  - Empirical testing provides a higher degree of confidence in the robustness of our sensing system as it takes into account real-world phenomena that FEA or first principles could neglect.

- Limitations:
    - The bumper parts manufactured by Shape Corp. exhibit variability from one part to another. Therefore, if the sensing system endures the 50 kN threshold but approaches failure closely, a variance in a new bumper could potentially lead to system failure
        - This is unlikely as our engineering analysis and research predicts our sensing system to survive well beyond the 50 kN mark.

Specification 3: Provide requested deflection data within 4 minutes of tested impact.

- Analysis Performed:
    - The algorithm processes data from 6 sensors within 30 seconds, and it is expected to have the capability of running through a larger number of sensors within 4 minutes, though this has not been tested.
- Justification:
    - Processing times for algorithms are generally consistent when run multiple times with similar inputs and our algorithm has been consistently fast.
    - We expect our timing of the processing time to be relatively accurate for future runs with real data.
- Limitations:
    - The processing time may change depending on the processing power of the computer that runs it.
        - While the integration of our system and algorithm into the vehicle computer is outside of our scope, it is still worthwhile to consider that processing time may be different for future computers using our system than the times of the computers available to us.

Specification 4: Sensors should operate between -40 and 140°F.

- Analysis To Be Performed:
    - This verification has not been completed, and would involve testing the bumper in a temperature controlled environment that could induce temperatures between -40°F to 140°F.
        - Our project's focus was to develop a sensor system that could function under the regular ambient temperatures experienced during testing.
- Key Results:
    - Future analysis from Shape Corp. would verify that the operating temperature range provided in the spec sheets of the sensors selected survive and accurately output data under those conditions.
- Justification:
    - Our project emphasized education alongside the primary objective of validating the system to meet the sponsor's task.

    - Future work will build upon the achievements of this class, potentially expanding the project beyond its current scope.
- Limitations:
    - Timing constraints: Testing under these conditions would require locating a facility that can replicate both the upper and lower temperature bounds and we did not have the time to do so.

Specification 5: Tools needed for installation be limited to those provided with purchase of sensor and those available in University of Michigan machine shop. Use ≤1 type of adhesive.

- Analysis Performed:
    - Installed the sensors using the method recommended by our sponsor and research of sensor installation.
    - Determined what tools were needed, and noted that they can be found in the aforementioned machine shop.
    - Performed testing on the assembled part to confirm that the installed system withstands testing.
- Key Results:
    - The adhesion held under testing
- Justification:
    - Performing 3-point bend testing on the assembled system will ensure that using the one adhesive type and catalyst from the kit is sufficient for adhering the system, thus verifying that ≤1 type of adhesive can be used.
    - Installing the system and verifying the parts are easily accessible also addresses the specification that the tools be available at the machine shop.
- Limitations:
    - There were no limitations with this analysis.

Specification 6: Take up less than 15% of surface area available on the specified part. System should protrude <25 mm from the surface of the part.

- Analysis Performed:
    - Measured the surface area of the strain gauges, flex sensors and the 8in span of the bumper structure that we are considering to verify that our preliminary calculations using the product specification sheets are accurate.
- Key Results:
    - The amount of surface area available in the 8in span we are considering is 19,304mm^2.

Table 13.1: Surface Area Occupied by Each Sensing System

Sensor Type	Number of Sensors	Surface Area of X Sensors [mm^2]	% of Available Surface Area
Flex Sensors	5	542.3	14.0
Strain Gauges	6	5.1	0.2

- Justification:
  - Measuring the surface areas would confirm that our initial analysis was accurate and that our sensors will not interfere with neighboring components or take up a significant amount of space on the bumper structure.
- Limitations:
  - Resolution of ruler used to measure the sensors and part is 1mm

14. Validation Plan

i. Verify Each Engineering Specification is Met - April 4th

- Verification processes were completed by April 4th, 2024 and the results of those processes are outlined above.

ii. Integrate Final Design for Validation Testing - April 7th

- Our final design outlined in **Section 12.iii** was applied to two more bumpers at Shape Corp.'s test facility, and were prepared for a 50 mm offset three point bend test.
- At this time our data processing algorithm was completed and functional.

iii. Final Testing - April 8th

- Shape Corp. performed final testing of the two bumpers prepared. The tests were identical to the initial rounds of testing, except that the prescribed deflection occurred at a 50 mm offset from center.

iv. Validation of Design - April 28th

- Shape Corp. identified a need to reduce the time and resources required to quantify the structural deformation sustained by a vehicle after a collision. By performing final testing we have validated that their goal has been met.
  - Deflection is measured up to 150 mm with maximum error of 17%.
  - Sensing system survived and collected data up to the maximum load experienced during the test, 35 kN.
  - Algorithm obtains accurate deformation data for 6 sensors within 30 seconds.

v. Beyond Our Scope

The scope of our ME450 project is confined to the central 8 inches of the bumper. Upon successful validation of our scope by Shape Corp. before the semester's end, the company will proceed to incorporate the sensing system throughout the entire bumper. Hence, it is important to emphasize that Shape Corp.'s overarching objective depends on the initial validation of our sensing system's performance within the central 8 inches. Upon achieving this validation, Shape Corp. expresses confidence in expanding the system to encompass the entire component.

15. Project Plan

This section of the report will outline the project plan as well as discuss the scope, critical tasks, and other considerations such as budget and time. **Figure 15.1** outlines our ten most critical tasks that we will need to achieve throughout the semester.

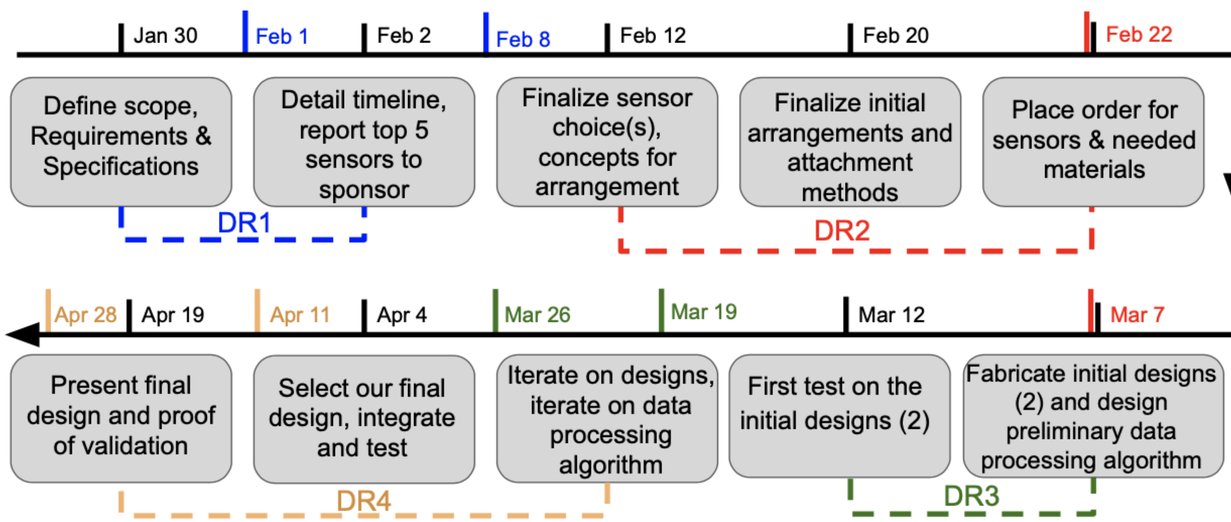


Figure 15.1: The timeline shown above walks us through the ten most critical tasks throughout the semester. The dates in which these tasks will be completed are given alongside the black ticks, the color coded dashed lines connect the tasks that need to be achieved for each design report, and the color coded ticks correspond to the design report due dates: the first tick being the presentation and the second tick being the report.

A more detailed project plan is given in **Appendix A** where we have each task identified throughout the entire project. Note that these tasks and the timeframe are subject to change in response to any scope changes, or potential challenges that arise throughout the semester.

i. Completed Milestones

1. Narrowed concept generation to two alpha designs
2. Fabricated and tested two alpha designs
3. Designed two preliminary processing algorithms for each design

4. Selected strain-based design as our final design
5. Completed validation testing for strain gauge design

ii. Contingency Plan

Sensor selection was a key part of the success of our project. We understood that modifying the arrangement and attachment method would have minimal downtime, but changing sensor types later would have been challenging due to the need for different data outputs and processing algorithms for different sensors. For this reason and due to the constraint of lead times if we encountered issues down the line, we ordered two types of sensors initially to provide options and fail safes. In the event that our sensing system was unable to survive a test, we would have considered new placement and/or attachment strategies, or use of the alternative sensor we had ordered. We attached our sensors to multiple bumper structures so that if we encountered issues with our first round of testing, which we did as the solders failed under loading, we would have other testing opportunities. We gave ourselves time to test more than once but only visited Shape Corp's facilities once to perform in-person testing.

iii. Budget and Time Considerations

- Our sponsor prioritized functionality over cost in this technology exploration project. While budget concerns for our project scope were minimal, we aimed to minimize costs to facilitate scalability during mass production.
- Our tight timeline led us to streamline the project scope, focusing on essential and secondary requirements. This approach ensured we met Shape Corp.'s primary goals within a realistic timeframe, with the opportunity to exceed expectations based on project success and progression.

16. Discussion

i. Problem Definition

If we had more time and resources to collect data and better define the problem, we would explore the following questions:

- Why are there discontinuities between FEA strain and real life data?
    - The element size could differ from the strain gauge active length. If these are drastically different, then the FEA readings may not be representative of the local readings from the gauges.
    - Our system analyzes local strain, but the FEA may be capturing global strain. This would pose issues if the strain on the bumper is non-uniform.
- How does the spacing of the strain gauges translate to accuracy of the strain curves generated?
    - Will reducing the spacing between sensors increase the accuracy of the strain curves, and will it give more insights to discontinuities on the strain curves?

- Does our algorithm still provide deformation data within the time allotted from our specification (4 minutes) if sensors span the entire bumper?
    - In the future, our system will need to obtain data from a large number of sensors, so would our algorithm provide data within 4 minutes given many inputs?
        - We currently estimate that our algorithm has an $O(n^2)$ worst-case time complexity with respect to the number of sensors. This means we could likely increase the number of sensors by at least 3 times while staying under a 4 minute processing time, without additional changes to the algorithm. Additional testing will be required to verify if this is the case.
- What other sensors (or combinations of sensors) could we use for this project?
    - Time constraints led us to narrowing into top sensor choices early on in the project. With more time, we could have explored more options, potentially leading to a more innovative solution.
- Can we use our deformation data coupled with the FEA to back out force?
    - First principles equations prove that force can be backed out from deformation, but will this hold true in our project?
- What tests other than a three-point bend test could be done to challenge the algorithm?
    - Different impacts on the bumper could lead to different results and challenge us to make a more robust algorithm.

ii. Design Critique

- Strengths:
    - Uses commonly found and readily available sensors and adhesives
    - Algorithm scales favorably with increased number of sensors
    - Easily adapted to other structural components
    - Withstands large forces experienced in a crash
- Weaknesses:
    - Relatively meticulous and time consuming to install, especially for future integration onto the entire part
    - Can’t identify collisions from other directions (side impact, etc)
- Improvements:
    - By converting to multiaxial strain gauges, our design could provide deformation data from more than just one direction.
        - This would involve making changes to the algorithm to process multi-axial strain data
    - With certain alterations of the algorithm, it would be able to determine both the degree of displacement and the location of the applied force.
    - Performing more analysis could allow us to create an analytical model that uses solid mechanics to relate strain to displacement. This would require a complex analysis of the strain and bending behavior of the bumper.

    - Algorithm could be improved to identify side impacts.
    - Refine the FEA to be more representative of the local strain experienced to create a better correlation between FEA and real world scenario. This would allow our algorithm to use both in tandem to create a more robust and accurate model.
    - Develop a more aesthetic, user-friendly interface in our design for easier data interpretation and usability of an unfamiliar operator. Our algorithm having to get data from one program and then be uploaded to MATLAB was fine for our sponsor's needs, but for anyone other than a test engineer familiar with the design, it may be hard to pick up and use quickly and correctly.

iii. Risks

- Sensors becoming detached from the part
    - Sensors from the very first test became detached, so during our build design, we took extra care to follow the adhesive manufacturer's guidelines to strongly attach the sensors. We never had any fall off in subsequent tests
- Data acquisition from the sensors
    - Thin wires relying on precise solder connections added risk that the sensors would not transmit data through the entire test. We switched to strain gauges with pre-installed wires to minimize this risk.
- If the end user at Shape Corp. has an issue with the code it may be difficult to resolve without knowledge of how the code was built.
    - Our algorithm's author added descriptive comments to the code which made it more user-friendly and understandable to someone who did not write it
    - Shape Corp. hired the member that built the code so they can email him if something breaks

17. Reflection

i. Public Health, Safety and Welfare

- Could allow for improvements to the structural integrity of automotive components, therefore enhancing vehicle safety.
- By ensuring the reliability and durability of our design, we contribute to the overall well-being and safety of vehicle occupants.

ii. Global Context

- Could benefit a global marketplace by providing a standardized solution for enhancing automotive safety across different regions and countries.
- Universal need for vehicle safety improvements; our design has the potential to address safety concerns in diverse automotive markets worldwide.

iii. Potential Social Impacts

- Our sensing system being adapted on a widespread scale could cause crash investigation companies to downsize and/or retrain workers to use new technology.

iv. Potential Economic Impacts

- Manufacture, use, and disposal of our design may increase the cost of cars for future consumers.
- Should our design advance to subsequent stages, Shape Corp. stands to gain a competitive advantage over its competitors.
- Shape Corp. could possibly partner with the sensor providers, leading to economic growth and stability for both companies.

v. Basic Tools Used

- We made a stakeholder map to identify relevant resource providers, status quo supporters, complementary organizations, beneficiaries, opponents, and affected or influential bystanders.

vi. Cultural, Privilege, Identity, and Stylistic Influences

- Similar cultural backgrounds between team members enabled effective communication; however, it narrowed our decision making process and potentially limited some different approaches.
- Our sponsor being an engineer facilitated effective communication with team members, all of whom were also engineering professionals. This enhanced mutual understanding of each other's needs and streamlined the problem-solving process.

vii. Inclusion and Equity

- For several team members, it marked their initial exposure to a professional setting and navigating the power dynamics inherent within a corporate environment.
- We prioritized Shape Corp.'s vision by actively seeking feedback from them and incorporating it into our design to make a solution that best fit our sponsor's needs.
- We promoted open dialogue and inclusivity within the team, and we were sure to enjoy each other's company alongside working together.

viii. Ethics

- In our project scope, we had to find a balance between incorporating additional sensors for enhanced performance and ensuring the affordability of our design. While increasing the number of sensors would undoubtedly improve the design, it also comes with increased costs.
- In the future considerations, the issue of data accessibility arises, including potential concerns about law enforcement access or the driver's privacy. Are we developing a

system that could potentially betray its users? We must avoid inadvertently facilitating increased surveillance or intrusion into personal lives.

18. Recommendations

Based on our experiences in the project, we have some detailed-level recommendations and system-level next steps for anyone continuing work on this project.

i. Risk Mitigation Strategies

Table 18.1: Risks and Potential Solutions

Sensors becoming detached from the part	Low risk, but if sensors become detached then switch to a stronger adhesive, or avoid particular application spots that experience sharp bend angles
Data acquisition from the sensors	Risk has already been mitigated by using pre-installed wires
Resolving issues with algorithm code	We don't believe there will be issues with the code as there are comments throughout explaining the algorithm. If issues do arise when expanding sensor system to entire bumper, then Shape Corp. can contact the person that developed the code

ii. Next Steps:

- Eliminate discrepancies between real world observations and FEA predictions
    - This would improve accuracy of the model
- Expand our design across the entire bumper
    - This would require increasing the number of available of DAQ ports
- Update the algorithm to use a larger number of sensors
- Enable the sensors to record and upload data to the cloud without reliance on wired connections to a static machine
    - This will allow for the system to be tested in more extreme scenarios that may not have a typical deformation pattern
- Apply our design to other structural components of the vehicle
    - This will allow for an x-ray like vision of the structural damage to a vehicle after a crash

19. Conclusions

- Current Methods of Accident Reconstruction
  - Require post processing to yield detailed data analysis
  - Are expensive or time consuming processes
- The Desired Outcome
  - A sensing system solution that delivers component deformation and force data minutes after a car crash
    - Streamlining the investigative process
    - Advancing Shape Corp.'s commitment to safety assessments
- Major Stakeholders
  - Shape Corp. and it's direct competitors
  - Automotive manufacturers
  - Sensor manufacturers
- Highest Priority Requirements
  - Measure deflection of the structural component after applied load
  - Withstand the crush and bending force applied to the provided component
  - Obtain sensor data from the part quickly after impact
  - Operate in various environmental conditions experienced by a vehicle
- Anticipated Challenges
  - Sensor availability - resolved
  - Product shipping - resolved
  - Time conflict for testing - resolved
- Concept Exploration Process
  - Concept generation through design brainstorming and functional decomposition
  - Concept development using functional decomposition eliminations, design heuristics, and morphological chart creation
  - Concept selection through eliminations of morphological concept combinations
  - Two alpha concepts selected through Pugh chart analysis
- Engineering Analysis
  - Thorough engineering analysis for each specification
  - Design iteration based on analysis and new information
- Build Designs
  - Through research, engineering analysis, and FEA simulations, we have designed and implemented two build designs integrating strain gauges and flex sensors
  - Two algorithms, each tailored to each specific sensor type to quantify structural deformation
- Final Design
  - After testing our two build designs and calibrating the flex sensors, we have determined that the strain gauge-based design is the most viable.

- Verification
    - Through empirical testing and verification against key specifications, we were able to verify that our final design meets our design requirements
    - The only exception to this is our operating temperature requirement. We did not have the resources to test this, but Shape Corp would be able to test this in the future.
    - We will select the best design as our final design, and proceed with validation
- Validation
    - Validation plan outlines the final steps, culminating the integration of our final design onto additional bumpers and validation testing at Shape Corp.'s facilities
    - Upon successful validation, we anticipate our sensing system to provide a streamlined solution for quantifying structural deformation post-impact
- Beyond Our Scope
    - Our scope is confined to the central 8 inches of the bumper; however, Shape Corp. recognizes the potential for scalability beyond our initial validation
- Discussion
    - Our discussion section outlines potential areas to explore to improve our design, as well as identifies strengths, weaknesses, and risk.
- Recommendations
    - Future work includes investigating the discrepancies between the FEA and physical test data
    - Design and algorithm can be further developed and applied to different parts and impact situations

Overall, our collaborative efforts with Shape Corp. and other stakeholders have paved the way for a sensing system that not only meets immediate needs but also lays the groundwork for future advancements in accident reconstruction and vehicle safety assessments. We remain dedicated to delivering a solution that promotes safety, sustainability, and inclusivity in the automotive industry.

20. Team Member's Autobiographies

Ethan Haire

I am from a small town called East Tawas that is about three hours north of Ann Arbor and located right on Lake Huron. I grew up playing many sports: hockey, soccer, golf, and baseball. I was always interested in cars as a kid - how they work, how to fix them, and how to improve them. This sparked my interest in being a mechanical engineer. I graduated top of my class and was accepted into the University of Michigan in the year 2020. Due to the COVID-19 pandemic I had to complete my first year online, but the remainder of my time in college has been here on campus. I enjoy mechanical engineering as it allows the fascinated kid in me to come to life when I am able to solve engineering problems and work with mechanical systems. Outside of engineering I enjoy weightlifting, reading the Bible, hanging out with my friends, and spending time with my cat, Luna. My future plans are to get involved in the automotive industry and work my way up to designing cars and trucks. I also plan to rebuild an old Detroit muscle car once I am out of school and have a good foundation. I hope to stay in south-east Michigan because my friends are down here, the automotive industry is down here, and I can stay connected with the Ann Arbor community.

Zach Cary

I am from Macomb, Michigan. I have an interest in mechanical engineering because I like understanding how the world works and why things are the way they are. I like knowing the physical as well as social and philosophical reasons for why problems exist. My future plans are to get a job in the automotive industry to apply my engineering skills and background gained at the University of Michigan. I hope to always provide great engineering work that benefits society and/or end-users to the fullest extent possible. I hope my work can contribute to liberty, freedom, and dignity. Some things I am passionate about outside of engineering are: photography, weight-lifting, plants, video games, longboarding, motorcycles, biblical readings, and issues related to human rights violations. Something I would like to explore professionally and/or personally is ways for people to grow their own food, generate their own electricity, and obtain water without toxic chemicals such as fluoride or lead. I am a strong proponent of autonomy and privacy, and I fear we are entering a world like that of 1984.

Sarah Multer

My name is Sarah Multer and I am from Merrick, New York. I love listening to music, reading, and playing sports. Growing up I played soccer, softball, and basketball on community teams, and I participated in a few aerial arts performances in summer camp. Currently I am a member of the Michigan Quadball (previously “Quidditch”) Team and a coxswain on the Michigan Men’s Rowing team. I have always preferred hands-on learning and I wanted to understand why products that we see in everyday life work the way they do or were designed as they were. I began studying mechanical engineering so that I could take advantage of the variety of jobs and applications that are available to me and I have been taking advantage of my ability to study material from various concentrations (such as Design & Manufacturing, Thermal Sciences, or Dynamics & Controls) beyond the core curriculum. I hope to explore positions in the automotive or theme park entertainment industry where I can work on consumer cars or roller coasters, respectively. In the future, I want to work on a roller coaster car/restraint system that is suitable for individuals of varying heights or figures, and to travel to every continent.

Ethan Fonger

I’m from Kalamazoo, about 100 miles east of Ann Arbor. Growing up, I was very curious about how things worked, often messing around with electronics around the house and taking apart my toys to find out what was inside. I always had an intense interest in all things space, constantly reading books about planets, astronauts, and rockets. These interests are what put me on my path to becoming a mechanical engineer, so I could learn how and why the things around me do what they do, and to contribute to the design of the machines that I’ve always found so interesting. My career aspirations involve working on the mechanical side of the aerospace industry, and a lifetime goal of mine is to somehow contribute to the space industry. I’m also interested in automotive and green energy technologies. I’ve had a lifelong interest in video games and computers, which prompted me to pursue a minor in computer science and take up game design projects in my free time. Outside of engineering, I enjoy working out, playing video games, reading, cooking, and learning new skills like the guitar. I love my home state of Michigan and hope to work here permanently in the future.

21. References

[1] *Shape Corp. | Lightweighting leader*. (n.d.). https://www.shapecorp.com/

[2] Corp, S. (2001, April 13). *Toyota Excellent Quality Award for Shape Corp. | Shape Corp.* https://www.shapecorp.com/toyota-excellent-quality-award-for-shape-corp/

[3] Corp, S. (2001a, March 18). *General Motors Names Shape Corp. a 2021 Supplier of the Year | Shape Corp.* https://www.shapecorp.com/general-motors-names-shape-corp-a-2021-supplier-of-the-year/

[4] *ENGINEERING | Shape Corp.* (n.d.). https://www.shapecorp.com/engineering/

[5] *MANUFACTURING | Shape Corp.* (n.d.). https://www.shapecorp.com/manufacturing/

[6] ADVANCED PRODUCT DEVELOPMENT | Shape Corp. (n.d.). https://www.shapecorp.com/engineering/apd/

[7] Accident reconstruction | BRC Online. (2022, March 24). BRC Online. https://brconline.com/services/accident-reconstruction/

[8] Voitel, T., & Terpstra, T. (Kineticorp, LLC). (n.d.). Benefits of 3D Laser Scanning in Vehicle Accident Reconstruction. https://media.faro.com/-/media/Project/FARO/FARO/FARO/Resources/2021/01/15/22/32/Whitepaper-Benefits-of-3D-laser-scanning-in-vehicle-accident-reconstruction-ENG.pdf?rev=7e724c48f9624ae3bd2a7b393c8fe394

[9] Applied Technical Services ATS. (2023, September 29). 3D Laser Scanning - Applied Technical Services. Applied Technical Services. https://atslab.com/litigation-support/3d-laser-scanning/

[10] Wynn and Clarkson - Models of Designing (2005)

[11] Cross N (1994) Engineering design methods: strategies for product design.

[12] ME Capstone Design Process Framework slides, Design Process Learning Block

[13] Schwartz, A. (2021, January 22). So-called “Consent searches” harm our digital rights. Electronic Frontier Foundation. https://www.eff.org/deeplinks/2021/01/so-called-consent-searches-harm-our-digital-rights

[14] Team, R. (n.d.). Sirius XM Connected Vehicle Makes Innovative Program Available to Automakers, Sending Vehicle Crash Data to 911 through RapidSOS to Help First Responders Save More Lives | RapidSOS. RapidSOS. https://rapidsos.com/our-latest/siriusxm-connected-vehicle-rapidsos-collaboration/

[15] NHTSA: Traffic crashes cost America $340 billion in 2019. (2023, January 10). NHTSA. https://www.nhtsa.gov/press-releases/traffic-crashes-cost-america-billions-2019

[16] Code of Ethics | National Society of Professional Engineers. (n.d.). https://www.nspe.org/resources/ethics/code-ethics

[17] INCLUSION | Shape Corp. (n.d.). https://www.shapecorp.com/inclusion-advisory-board/

[18] SUSTAINABILITY | Shape Corp. (n.d.). https://www.shapecorp.com/corporate-responsibility/

[19] Van Eikema Hommes, Q. D. (2016, June). Assessment of safety standards for automotive electronic control systems. (Report No. DOT HS 812 285). Washington, DC: National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.gov/files/812285_electronicsreliabilityreport.pdf

[20] Online materials information resource - MatWeb. (n.d.). https://www.matweb.com/

[21] Beam Stress & Deflection | MechaniCalc. (n.d.). https://mechanicalc.com/reference/beam-analysis

[22] Electrical Circuit Basics | 12 Volt Planet. (n.d.). https://www.12voltplanet.co.uk/electrical-circuit-basics.html

[23] Omega Engineering | Linear Strain Gauges (n.d) https://www.omega.com/en-us/force-and-strain-measurement/strain-gauges/linear-strain-gauges/sgd-linear1-axis/p/SGD-2-350-LY11

[24] Amazon | Pre-Soldered Accelerometer for Raspberry Pi and Arduino (n.d). https://www.amazon.com/Pre-Soldered-Accelerometer-Raspberry-Compatible-Arduino/dp/B0BMY15TC4

[25] Spectra Symbol | Flex Sensor (n.d). https://store.spectrasymbol.com/products/flex-sensor?variant=40666458488947&currency=USD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&https://www.spectrasymbol.com/resistive-flex-sensors&gad_source=1&gclid=Cj0KCQiAw6yuBhDrARIsACf94RUE3y3elhF3swJA3fCq9HcYoZtAVsMlkRNylVyfYGuMfgzcXcxUmUMaApUUEALw_wcB

[26] Uline: Heavy-Duty Adhesive Transfer Tape (n.d). https://www.uline.com/Product/Detail/S-8409/Adhesive-Transfer-Tape/Uline-Heavy-Duty-Adhesive-Transfer-Tape-1-2-x-18-yds?pricode=WB1078&gadtype=pla&id=S-8409&gad_source=1&gclid=CjwKCAiAuNGuBhAkEiwAGId4avrqMRe_y-_B8ALHKjmwbDI4o6Hq2wTA7hq1MyyQK53dHxqQ1aUNyxoCrcAQAvD_BwE

[27] Micro-Measurements | Technical Documentation (n.d). https://docs.micro-measurements.com/?id=6671&_gl=1*jx3yqh*_ga*MzE1MjA1ODEuMTcwODAyNjc4Nw..*_ga_PJJTYL5W9L*MTcwODAyNjc4Ni4xLjAuMTcwODAyNjc4Ny41OS4wLjA.&_ga=2.101238465.1987662430.1708026787-31520581.1708026787

[28] RapidDirect | Types of Fasteners https://www.rapiddirect.com/blog/types-of-fasteners/

[29] Ullman, D. G., Wood, S., & Craig, D. (2012). Design Heuristics for Mechanical Engineering: A Cognitive Approach. In ASEE Annual Conference Proceedings. https://www.designheuristics.com/wp-content/uploads/2012/08/3_ASEE_2012.pdf

[30] Hu, S., Wang, Y., Wang, C., Pu, W., & Qiu, L. (Year). Realization Method of Sensing-Integrated Fishbone With Deformation Monitoring Based on Screen Printing Technology. https://ieeexplore-ieee-org.proxy.lib.umich.edu/document/10341293

[31] Spectraflex. (2021). SPECTRAFLEX DATA SHEET v1.0 [Brochure]. Shopify. https://cdn.shopify.com/s/files/1/0578/4128/7283/files/SPECTRAFLEX_DATA_SHEET_v1.0.pdf?v=1691015077

[32] Massachusetts Institute of Technology. (n.d.). Polyimide Material Properties. Retrieved from https://www.mit.edu/~6.777/matprops/polyimide.htm

22. Appendix A

Timeline:

Legend: Sponsor Deadline, Class Deadline, Internal Deadline, Testing

Friday, Feb 2:

Deliverables: Top 5 sensors, Detailed Timeline, FEA Decision, Updated Scope Doc, DR1 Presentation (Due Thursday, 2/1)

Next Week's Focus: Review sensor data to narrow down to final 3, Complete DR1 Report

Thursday, Feb 8:

Deliverables: Problem Definition Report [DR1] (Due Thursday, 2/8), Top 3 sensors, Discussion in meeting to finalize choice (or integrate two)

Next Week's Focus: Determine best sensor, work on layout configurations

Thursday, Feb 15:

Deliverables: Best Sensors (2), possible arrangements

Next Week's Focus: Determine sensor arrangement on a specific part from Shape Corp, determine attachment method, contact sensor supplier for placing an order, DR2 presentation

Thursday, Feb 22:

Deliverables: Concept Selection Presentation [DR2] (Due Tuesday, 2/20), CATME Team Evaluation 1 (Due Thursday, 2/22), final arrangement and attachment method, place order for sensors/necessary materials

Next Week's Focus: Get ready for test at Shape Corp. in Grand Haven, MI

Thursday, Feb 29: SPRING BREAK, no meeting

Thursday, March 7:

Deliverables: Concept Selection Report [DR2] (Due Thursday, 3/7), proof of concept for initial two prototypes, initial data processing algorithm

Next Week's Focus: Fabrication deadline (Due Thursday, 3/7), tentative testing (Tues 12th)

Thursday, March 14:

Deliverables: Progress update on algorithm for data processing

Next Week's Focus: Tentative testing (Thurs 21st), process data, develop second prototype of the chosen design, DR3 presentation preparation

Thursday, March 21:
Deliverables: Initial Final Design Presentation [DR3] (Due Tuesday, 3/19), results from initial testing, second prototype
Next Week's Focus: process data, refine algorithm

Thursday, March 28:
Deliverables: Initial Final Design Report [DR3] (Due Tuesday, 3/26), CATME Team Evaluation 2 (Due Thursday, 3/28) results from second test
Next Week's Focus: Tentative testing (Tues 4/2), finalize design, Design Expo poster abstract (Due Tuesday, 4/02)

Thursday, April 4:
Deliverables: Majority of testing done,
Next Week's Focus: DR4 presentation

Thursday, April 11:
Deliverables: Proof of Validation Presentation [DR4] (Due Thursday, 4/11), Design Expo poster internal deadline
Next Week's Focus: Design Expo Poster completed and DR4 Report (Due Sunday, 4/28)

Thursday, April 18:
Deliverables: **Design Expo [Poster] (Due Tuesday, 4/16)**
Next Week's Focus:

Thursday, April 25:
Deliverables: Final Report [DR4] (Due Sunday, 4/28), Final CATME team evaluation (due 4/28)
Next Week's Focus: Graduate

23. Appendix B

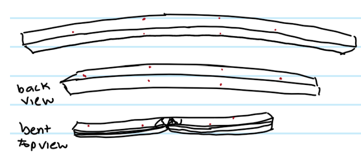
Concept Generation

Sensor Types:

1. Flex Sensors
2. Accelerometers and gyroscopes
3. Radar sensors
4. Miniature LiDAR sensors
5. Sonar sensors (ultrasound technology)
6. Carbon Fiber sensors
7. Linear Variable Differential Transformers (LVDT)
8. Potentiometers
9. Strain gauges
10. Photogrammetry images
11. CT scan x-ray imaging
12. Thermal imaging
13. Resonance frequency sensors
14. Piezoelectric sensor arrays
15. Smart shape memory alloys
16. Impact-responsive gel sensors

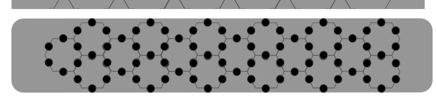
Sensor Arrangements/Locations:

1. External camera system in proximity of bumper beam structure
2. Hexagonal sensor placement across two faces of the beam ->

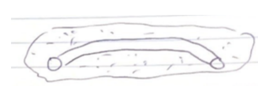


3. Sensors placed on the back of the beam
4. Sensors placed on the top of the beam
5. Linear arrangement of sensors along one face of the beam ->

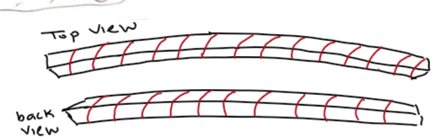
6. Triangular arrangements of sensors
7. Honeycomb arrangement ->



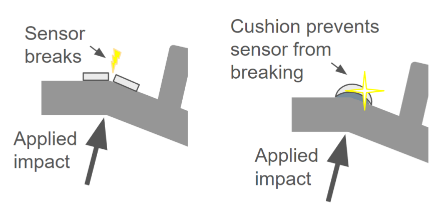
8. Position sensors closely-packed
9. Position sensors farther out and interpolate more
10. Sensing foam around the part ->



11. Sensors wrapped around the part ->



12. Internal, jointed structure with discrete bend sensors
13. Attach sensor to flexible or cushioning structure ->



Algorithm/Extra Ideas:

1. Wireless system that can notify authorities/user if a certain threshold is reached
2. Use sensors toward the center to "build" deformation working outwards, refining outer shape recursively: reduction in computation cost, change in accuracy?
3. Loss of data from sensor could imply that a certain sensor threshold has been reached, which the algorithm can take into account if need be
4. Continuously upload data in case of sensor failure during crash ← (last-uploaded premature data can be more useful than a broken sensor that doesn't upload anything at all after the crash)
5. Use data from past crashes to build databases and refine deformation estimates based on past data
6. Measure curvature at different points and interpolate to estimate deflection.
7. Measure position change at each point (Double integrate acceleration? Direct measurement?), interpolate (Linear? Quadratic? Cubic?) between points to estimate amount of deflection
8. Use larger and denser set of cheaper sensors rather than a fewer number of more expensive ones (even if some fail you'll likely have more working ones by the end))
9. Use different sensors depending on the expected scenario (accelerometers for high-acceleration crashes, strain gauges for slow, quasi static testing conditions)
10. Have sensors communicate with the sensor next to them to determine relative motion/position, instead of all communicating absolute position/motion data directly with the data collection computer
11. Attach flex sensors pre-bent so they can measure flex in both directions
12. Connect resistive-based sensors with one end on the metal part surface ← (acts as ground voltage to eliminate an extra wire in the voltage divider)
13. Use internal, jointed structure and measure bend (using bend sensors) in discrete joints

24. Appendix C

Bill Of Materials

Part No.	Part Title	Part #	Material	Dimension(s)	Supplier
1	Spectra Symbol Flex Sensors	FLX-L-0055-123-ST	-	55mm active length	Spectra Symbol
2	Strain Gauge	Item# SGD-3S/120-LY11	-	3mm grid length	Omega Engineering
3	Adhesive M-Bond 200	102559-100	-	N/A	Vishay Precision Group, Inc
4	Arduino	B0046AMGW0	-	N/A	Amazon

Quantity	Unit Price	Lead Time	Notes / Link to Purchase
1	$10.38 (bulk)	None, ship same day	https://store.spectrasymbol.com/products/spectraflex-flex-sensor?v
1 pack (10 sensors)	$108.05	4 weeks if not in stock	https://www.omega.com/en-us/force-and-strain-measurement
1 kit	$120.22	-	https://docs.micro-measurements.com/?id=6671&_gl=1*jx3yq
1	$48.90	None, overnight	vw.amazon.com/ARDUINO-MEGA-2560-REV3-A000067/dp/B004

Purchased Part No.	Qty	Price/Unit	Cost	Shipping
1	40	$10.38	$415.20	$6.90
2	4 packs (40 sensors)	$108.05	$458.13	$20.00
4	1	$48.90	$48.90	Free

25. Appendix D

Strain Gauge Prototype Algorithm Output Displacement Comparison

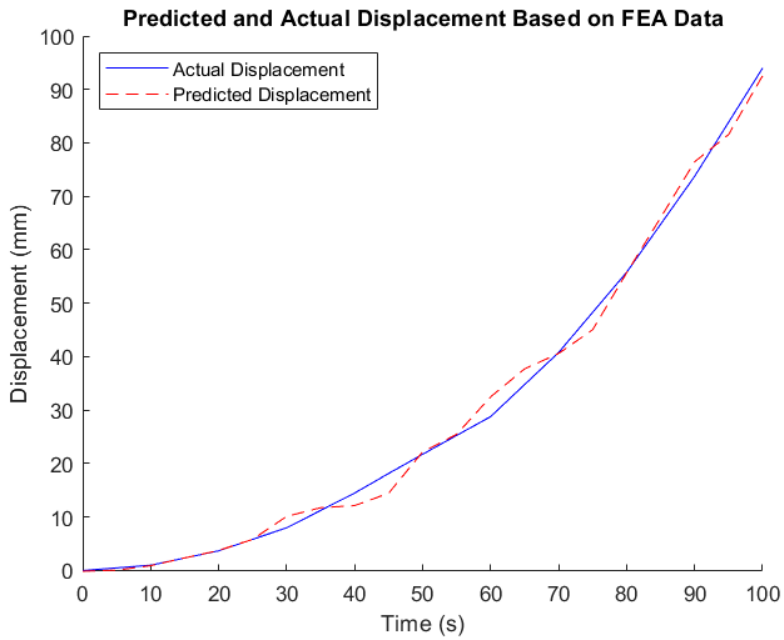


Figure D.1: Strain gauge algorithm-predicted displacement compared to actual displacement from the FEA data. The maximum error that was seen was 27%, but this was at a small displacement of 8 mm. No errors above 25% were seen at larger amplitudes of displacement.

Flex Sensor Prototype Algorithm Output Displacement Comparison

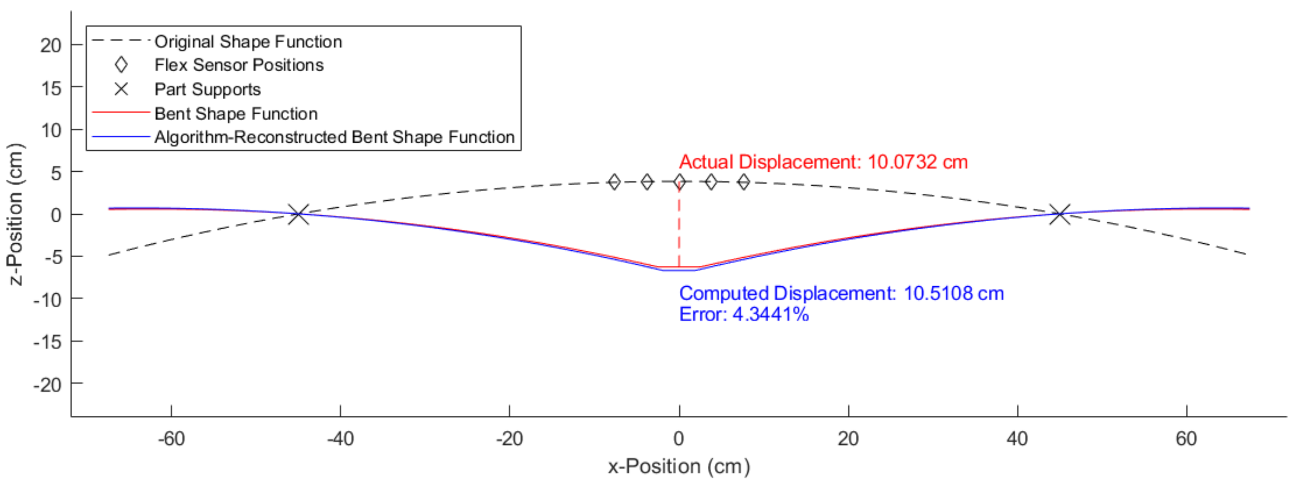


Figure D.2: Flex sensor algorithm-predicted displacement compared to the provided displacement from a sample bent shape function. Errors larger than 25% were seen only with displacements smaller than 12 mm. No errors above 25% were seen at large displacements, which generally had errors of less than 10%.

26. Appendix E

Manufacturing Plan of Final Design

1. Prepare the surface of the part to adhere Omega Strain Gauges
    a. Clean the surface that strain gauges will be adhered to using a degreaser: spray degreaser, then wipe with a cotton pad. Repeat until the cotton pad is clean after wiping. See **Figure E.1**
    b. Measure and mark the locations where the strain gauges will be adhered using the caliper. See **Figure E.2**
    c. Use sandpaper to roughen the surface of the part at each location. See **Figure E.3**
    d. Clean each attachment location again using the degreaser. See **Figure E.1**
2. Attach the strain gauges to the part using M-Bond 200 adhesive
    a. Attach the strain gauges to the part at each location using office tape, then peel the tape back. **Figure E.4**
    b. Use a brush to apply the adhesive catalyst to each of the attachment locations.
    c. Apply a small amount of the adhesive at the base of the peeled-back tape.
    d. Unroll the tape, reapplying the strain gauge to the surface, and apply pressure with a cotton pad for 1 minute to allow the adhesive to harden. **See Figure E.5**
    e. Remove the tape from the strain gauges.

Figure E.1: Application of degreaser. The degreaser would then be wiped using a cotton pad.

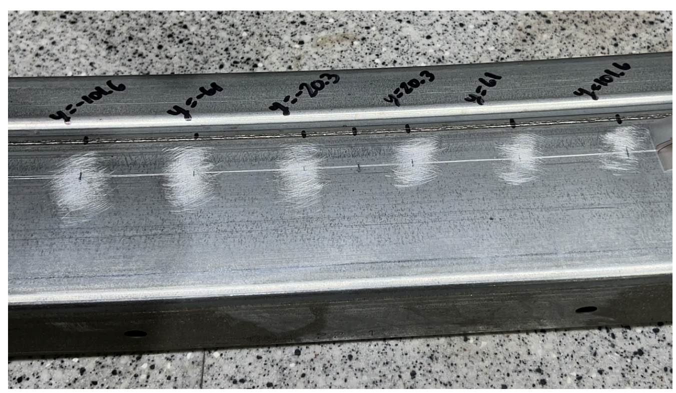


Figure E.2: Strain gauge placement locations measured and marked.

Figure E.3: Roughen the strain gauge placement locations with sandpaper

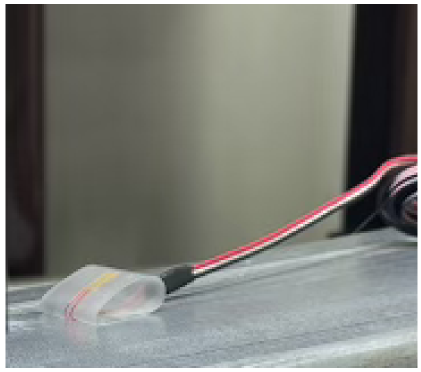


Figure E.4: Strain gauge attached to the part using tape, which is then looped back.

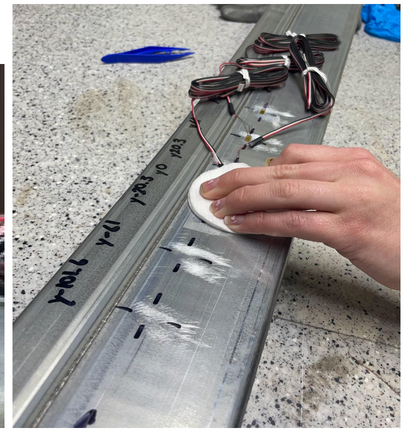


Figure E.5: Apply pressure to the adhesive location for at least 1 minute