Asian Research Association
INTERNATIONAL RESEARCH JOURNAL OF
MULTIDISCIPLINARY TECHNOVATION

DOI: 10.54392/irjmt2431

Mitigating Frame Cracks in Off-Highway Vehicle: A Combined Approach of Finite Element Analysis and IoT-based Chassis Health Monitoring System

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DOI: https://doi.org/10.54392/irjmt2431
Received: 02-02-2024; Revised: 17-03-2024; Accepted: 29-03-2024; Published: 05-04-2024

Abstract: A Heavy-duty cargo truck manufactured by the Chinese company SHACMAN X3000 is designed and analyzed in this paper. Here, this paper developed a Chassis Health Monitoring System (CHMS). The objective of the system is improving the safety measures by combining computational techniques using FEA on static structural and Modal analysis followed by experimental work by implementation of IoT for monitoring and validation purposes. In this paper, for analysis purpose, we selected four critical points based on the survey and underwent the analysis by computational tool. The CHMS consists of a Force sensor, a Flux sensor, and RGB with Arduino, which is to collect and analyze to monitor the frame. The analyzed results give the optimal value in the frame near the critical areas, which results the crack. The CHMS, it a pre-alert system and safe guard the chassis.

Keywords: Chassis Health Monitoring System (CHMS), FEA (Finite Element Analysis), Static structural analysis, Modal analysis, IoT (Internet of Things), Force sensor, Flux sensor, Crack detection, Pre-alert system

1. Introduction

Off-highway vehicles have become increasingly popular in recent years, used for transportation, and work in challenging terrain. Predictive maintenance in the automotive industry employs unsupervised machine learning and clustering to identify faults in tire, wheel bearings, and suspension system components, thereby reducing costs and enhancing safety [1]. The study utilizes finite-element (FE) models to analyze load-carrying capacities of stainless-steel CHS-to-SHS hybrid tubular joints, revealing geometric parameters significantly impacting capacities, and proposing modified design formulae [2]. Fault detection and fault diagnosis are crucial in vehicle control system design, enhancing efficiency, reliability, and performance through model-based methods for monitoring vehicle chassis performance. [3]. The study utilizes vibration sensors to detect damage in aircraft structures, highlighting the potential for early detection of potential flight hazards due to fatigue cracks and loose rivets [4]. The study introduces a data-driven method for detecting bridge damage using vibration signals from passing vehicles, utilizing dimensionality reduction techniques and stacked autoencoders for improved accuracy [5]. FEA Analysis is utilized to evaluate the strength and safety of the FSAE chassis frame, utilizing the AISI4130 alloy for its optimal strength and weight [6]. The paper presents a finite element model analyzing CFS built-up un-lipped channel sections under axial load, revealing that un-conservative stub and short columns failed due to local buckling [7]. The health monitoring system offers critical assistance through mobile monitoring, utilizing various sensors for monitoring vital signs and providing immediate medical care [8]. Autodesk Inventor 2017, FEA, and experimental methods were used to analyze the failure of a leaf spring in a dump truck vehicle suspension system, revealing a fracture [9]. The method utilizes vibrational response-only accelerometer information, a data-driven approach, and machine-learning algorithms to diagnose structural damage in jacket-type foundations for offshore wind turbines [10].

The Shacman Truck back to the mid-20th century, a time when China's nascent automotive industry was finding its footing. The study assesses leaf spring fatigue life reliability using strain loading data from three road conditions, revealing the Gumbel distribution as the most suitable for the highest fatigue life [11]. Condition monitoring is a crucial process in ensuring the health and safety of individuals, utilizing advanced technology and signal processing techniques to monitor and manage conditions effectively [12]. The FEM model accurately describes the hysteresis nonlinearity of a leaf spring in a heavy-duty truck, simplifying axles, powertrain, and cab and frame, thereby improving calculation efficiency and reducing model size [13]. Modal & Finite Element Analysis (FEA) is a crucial tool for predicting vibration in a vehicle's chassis, aiding in material selection, geometry selection, performance enhancement, assembly, and pilot safety [14]. FEA simulates structural behavior, identifying stress concentrations and weak points, optimizing design, and monitoring structural health with IoT for real-time anomalies, enabling timely maintenance and repair. MATLAB-SIMULINK is a powerful tool for integrating various models into a vehicle chassis, enhancing performance through enhanced suspension travel and acceleration [15]. The major cause that brings CHMS into off-highway vehicles is the Vehicle design, suspension specialization, frame complexity, and overall usage are crucial factors in operating in tough terrain, requiring aggressive driving and maintenance. Predictive maintenance is a crucial strategy in the automotive industry, utilizing sensor data to anticipate faults in fuel, ignition, exhaust, and cooling systems, thereby increasing vehicle up-time [16]. Structural detection is a critical process utilizing sensors to monitor traffic load and health, ensuring safety and efficient monitoring of various peaks [17]. The vehicle control system's reliability, efficiency, and cost reduction can be significantly enhanced through improved fault prediction, maintenance, strengthening monitoring, and health assessment [18]. The paper proposes a unique vehicle electrical monitoring system scheme that utilizes electronic communication networks and mechanical electronic units for state monitoring and maintenance in complex vehicles [19]. AISI 4130 material, known for its high tensile strength, is extensively utilized in vehicle chassis design, particularly in off-road vehicle (ORV) chassis for aggressive roll cage creation [20].

The above systems are highlighted with importance of predictive maintenance, structural detection, and robust electrical monitoring systems for complex off-highway vehicles. Such systems are essential to enhance reliability, safety, and efficiency in harsh operating environments. Moreover, these systems work best when coupled with strong materials like AISI 4130 steel, as frequently used in off-road vehicle chassis design. By prioritizing proactive maintenance, structural integrity monitoring, and advanced electronic systems, manufacturers of off-highway vehicles can optimize vehicle uptime and performance in challenging conditions.

Many other health monitoring systems have been developed from previous studies. However, the technique used to resolve the challenges is in two ways: computational and experimental. The proposed work focused on implementing a Chassis health Monitoring System for Off-highway vehicles by designing the conventional chassis and analyzing the chassis by Ansys workbench tool (different constraints & iterations) and MATLAB (different case & pictorial views). With its output data, it is programmed and embedded with Arduino to predetermine its failure and alert the driver.

2. Proposed Methodology

Figure 1 summarizes the sequence of steps followed in the form of a flow chart. The methodology involves designing and selecting a cargo Shacman chassis, analyzing critical points, performing Finite Element Analysis (FEA), selecting criteria based on industrial safety standards, using Ansys WorkBench and MATLAB software for computational techniques, and implementing a prototype of the Chassis Health Monitoring System (CHMS) to collect data on stress and vibration at critical points.

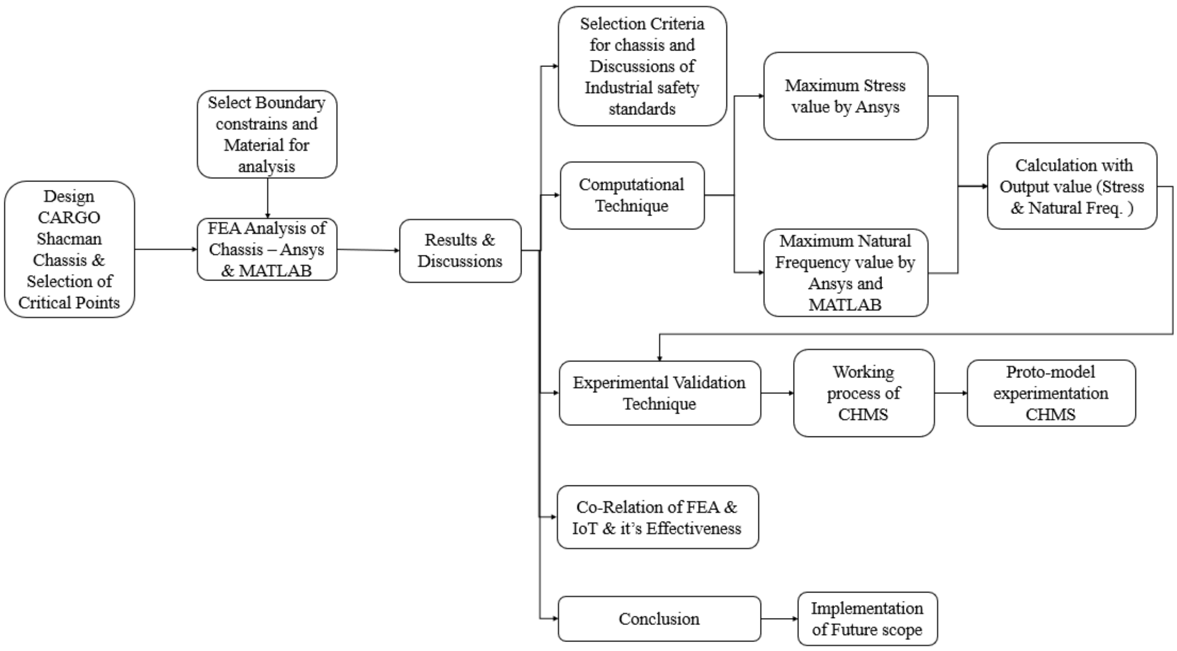

Figure 1. Methodology

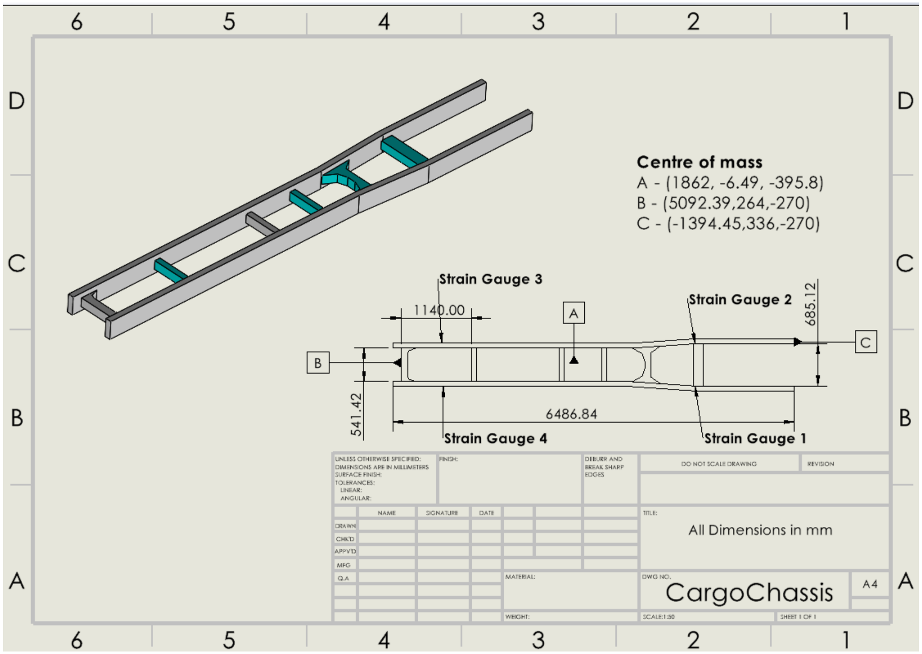

Figure 2. Design of Chassis with Critical Points

The FEA results and CHMS data are compared and analyzed to evaluate their effectiveness in detecting and preventing frame cracks. The study concludes that combining FEA and CHMS can improve the safety and reliability of off-highway vehicles, but specific details may vary depending on the application.

The FEA methodology involves designing the chassis, mesh generation, material properties, boundary constraints, static structural analysis, solving and analyzing results, integrating IoT sensors, and validating and refining. The results of both analyses are then combined and discussed.

The flowchart also includes an experimental work section, which involves using flux and force sensors with RGB lights and the use of Arduino microcontroller. This section is likely used to validate the results of the simulations.

Overall, The IoT-based Chassis Health Monitoring System effectively detects and prevents frame cracks in off-highway vehicles through real-time monitoring, early detection, predictive maintenance, condition-based alerts, and seamless integration with design processes.

2.1 3D Modelling and Selecting Critical Points in chassis

The Cargo Shacman X3000 Model chassis is designed from the Cargo model truck by SolidWorks software (All dimensions in mm). The Centre of mass (X, Y, Z) of the chassis A: (1862, -6.49, -395.8), B: (5092.39,264, -270) and C: (-1394.45,336, -270).

1. Strain gauge 1 mount in chassis at a critical point at position 1.
2. Strain gauge 2 mount in chassis at a critical point at position 2.
3. Strain gauge 3 mount in chassis at a critical point at position 3.
4. Strain gauge 4 mount in chassis at a critical point at position 4.

Figure. 2 shows the Cargo Shackman X3000 Chassis Frame. Vehicle chassis frame is designed, based on rough calculation. The leaf spring joint is mounted by the Strain gauge sensor bottom left clip (1) and lower right (2). In this design, the Leaf spring at the upper right joint (3) is attached to the strain gauge and the lower left end with the leaf spring joined (4).

2.2 Boundary Condition and Material Selection

The system was subjected to an external load. The mass load applied load of 1.4MPa (Pressure) & 600 N (Force).

Meshing: The regions where the boundary conditions are the points where the chassis ends are fixed. The meshed model of the chassis frame is shown in Fig 3. It is a uniform meshing that has several nodes 2978 and several elements 332, each with three translational DOFs. This is obtained through Automatic Method Control meshing operation. The static structural analysis was performed on the ANSYS workbench under external load conditions as per the sequence given in Figure 3.

Material Selection: In this analysis, the selection of materials and properties plays a vital role. Based on the survey [21], off-highway truck chassis use high carbon strong materials, so for simulation purposes, the selected material is High-strength structural steel

(IS1030). As shown below table 1 describes the material properties. The critical points are claimed from study survey work [22].

Fatigue Boundary constrain condition: Fixed on both sides $v = 0$ end for the assumption as shown in Figure.4a. The load applied to the chassis is 1.4 MPa & Force of 600 N. The fatigue life range is perpendicular to the weld and positioned in the chassis joint. It's about 500 MPa. This is the most essential location for all fatigue load scenarios. As shown below a) and b) are the boundary conditions as it represented in figure 4.

2.3 Development of Proto-model – CHMS

The chassis health monitoring system is the approached solution for the problem for all off-highway vehicles in terrain areas. We obtained the threshold value of Stress and Natural frequency (Vibration) in the last section. It is now followed to develop the system by hardware components: **a)** Arduino UNO R3, **b)** Resistors, **c)** Breadboard, **d)** Flex sensor**, e)** Force sensor, **f)** RGB LED, **g)** Piezo Buzzer, & **h)** Jumper wires.

3. Results and Discussions

Previously, we have approached the designing of chassis and initialized the boundary constraints in chassis through Ansys Workbench. In this section, discuss the work in two parts: Computational Technique and then followed by Experimental Validation for CHMS.

Computational Technique is a method approached by FEA analysis by ANSY Software and vibrational behavior based on several conditions by MATLAB. Then, the experimental method is based on the Internet of Things work by Arduino controller based on the Computational method.

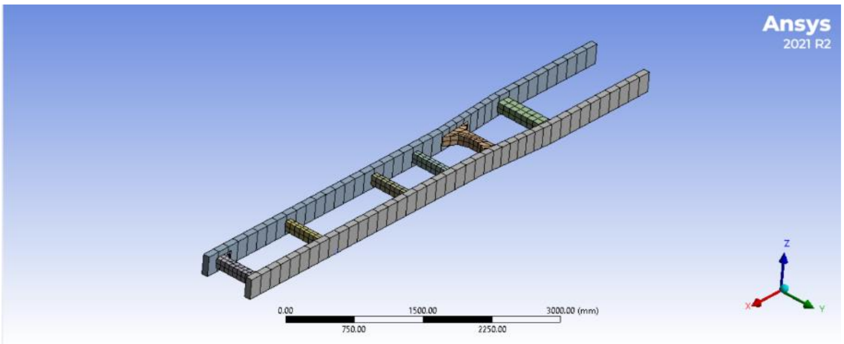

Figure 3. Meshing of Cargo Shacman Chassis

Table 1. Material properties of High-strength structural steel IS1030

S.No	Properties	Value
1.	Yield Strength	410 MPa
2.	Ultimate Tensile strength	520 MPa
3.	Poissons Ratio	0.30
4.	Density	7800 kg/m^3
5.	Modulus of Elasticity	200 GPa

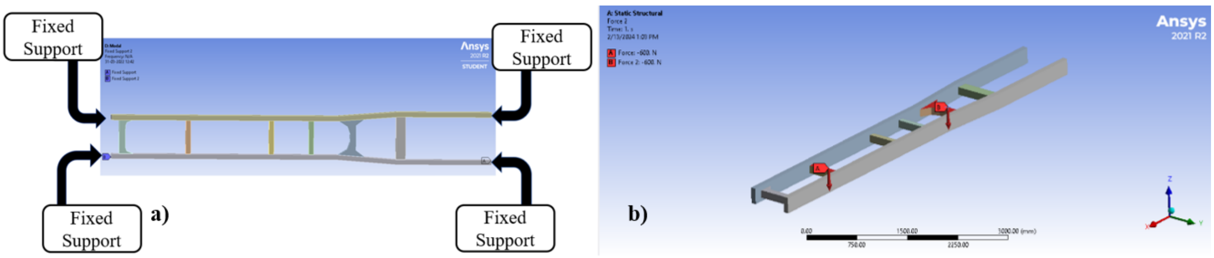

Figure 4. Selection of constraints for Analysis a) Fixed Support b) Mass load F= 600 N

3.1 Chassis selection criteria & Industrial safety standards

In this section, we discuss about the criteria and industrial safety standards in which the chassis have been designed and approached for the analysis followed by experimental work.

The CargoShacman dump truck chassis is a widely used model in the target industry, providing broader relevance and applicability to real-world scenarios. Its dimensions align with research objectives, such as payload capacity and maneuverability. The chassis's dimensions are also considered in related studies for consistency.

- Comprehensive technical specifications and detailed measurements are available for accurate modeling and analysis.
- Chassis dimensions align with research objectives.
- Overall length: 6486mm, width: 541mm, weight: 1700 kg.

Few industrial Standards are Influencing Off-Highway Vehicle Frame Crack Mitigation

- ISO 16750: Specifies environmental tests for road vehicle equipment.
- ISO 26262: Addresses functional safety of road vehicle systems.
- SAE J211: Provides instrumentation guidelines for impact testing.
- ASTM E1823: Provides fatigue and fracture testing terminology.
- Regulatory Standards: Ensures legality and market acceptance of combined frame crack mitigation vehicles.

These regulations are for off-highway vehicles in the road safety measures. These are industrial tests for frame crack identification through advanced technology.

3.2 Computational Technique

Computational Technique is the method of approach to discuss the static structural behavior of the chassis. By implementing the FEA method, this analysis gives the optimal value on Stress and Natural Frequency based on governing equations (1) & (2).

3.2.1 Static Structural Analysis

The results shown below are the output obtained based on the boundary condition and constraints. It is fully based on a theoretical method to obtain the optimal value of chassis with Eq. 1. As it is discussed, a computation technique is applied that followed to the next section in this paper, as we select von Mises stress and vibration to threshold value as major parameter.

After applying the boundary condition, the file is imported into the solver. The location of a) maximum deformation and b) maximum Von Mises stress is just near critical points as shown in Figure 5. The maximum Von Mises stress is about 116.8 MPa and the maximum deflection is about 3.899 mm.

The static analysis of the chassis frame was performed using ANSYS Workbench. We simulated the chassis based on boundary conditions and constraints, as we obtained high equivalent stress at critical 4 points in the chassis.

This selected critical area in the chassis frame is a key for the solution. By Eq (1) Mass force F_i is applied to the critical point areas A_i and the Maximum stress obtained in the chassis frame is shown in Table 2.

By obtaining the optimal value, it is noted down in 4 critical points as it is shown in Table 2.

$$|P| = \sum_i^{\infty} \frac{F_i}{A_i} \tag{1}$$

3.2.2. Modal Analysis

Modal analysis is used to determine the natural frequency and optimal vibrational value in the structures or components caused by steady loads.

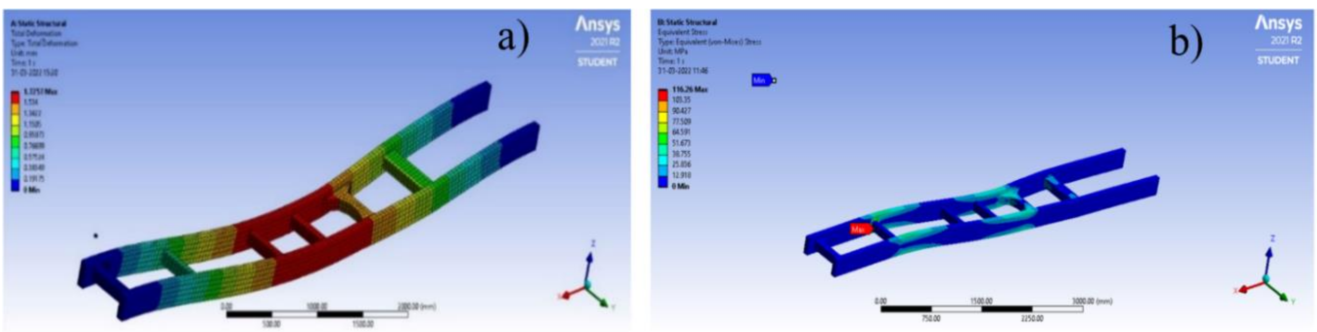

Figure 5. Static Structural Analysis of Chassis

Table 2. Location of Maximum Stress obtained in critical area

S. No		Location	MPa
1	Equivalent Stress	At Position 1	116.8
2		At position 2	114.89
3		At Position 3	100,.89
4		At Position 4	102.99

The study uses boundary conditions to apply load and define constraints in a model, with all degrees of freedom restricted at the fixed ends.

Finite element analysis is carried out on the modal analysis of the chassis frame. The Ansys Workbench was used to simulate the modal analysis. The results of natural frequencies and mode shape were obtained as shown in Figure 6.

Modal analysis helps identify structure modes characteristics, predict vibration response, and serve as a reference for dynamic analysis like random and harmonic analysis.

Each natural frequency of respective mode shapes is listed in the table 3. If any one of the natural frequencies matches with excitation frequency the frame doesn't satisfies the dynamic characteristics. Out of 6 mode shapes, the fourth to sixth mode shape with a natural frequency of 105.25 Hz to 164.83 Hz is critical and it will produce maximum stresses under dynamic conditions.

The obtained natural frequency through the Ansys tool is shown in Table 3 with Eq.2. Table: 4 shows the vibration of chassis in 4 critical point locations in which vibration / natural frequency of chassis occurs due to loads/conditions

$$f_k = \int \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (2)$$

The formula contains constant variables for mass 'm' and stiffness 'k' whose values are globally constant. The deterioration effect on the chassis will be indicated by the accelerometer sensor which is routed to the CHMS Module. As it attains the resonant frequency, it is subjected to a note down in theoretical threshold value. Here we use MATLAB simulation for a deliberate pictorial view of chassis in different scenarios.

As a result, this analysis follows the Beta Newmark method (assumption: three degrees of freedom) to show the complicated vibration analysis in the machine that contains its own natural frequency, resonance, and damping nature.

From the obtained results in Table 2 and Table 4, the following Arduino Microcontroller system monitors the critical area and pre-detect the result. These four corners are critical areas, mounted by Flex and force sensor.

3.2.3. Computational Calculation

As we have used Ansys Workbench for simulation we have demonstrated through virtual simulation by obtaining the threshold value of pressure 116 MPa and vibration 104 Hz. In detail, we simulated through MATLAB Simulink for different circumstances for predicting its vibrational behaviour ($\mathrm{F_k}$ lies between 80 Hz to 150 Hz) graphically demonstrated.

Let's consider that $\mathrm{f_p}$ 25 Hz is the threshold value (consider in stationery mode) for natural frequency,

As when the vehicle bumps on the road, the stress is induced into the chassis say 110 MPa. Let the mass of the chassis be 1700 kg, critical surface area is 1.62 m² [cross-section area A: 6.48 x 0.25 m], and Young's modulus is 200 GPa and stiffness k?

$$\mathrm{k} = \frac{\mathrm{A_i E}}{\mathrm{l_i}} = 1.62 \text{ x } \frac{200\text{x}10^9}{6.486} \approx 49 \text{ GPa} \qquad (3)$$

Then, using the natural frequency formula from Eq.2.,

$$\mathrm{f_t} = \int \frac{1}{2\pi}\sqrt{\frac{\mathrm{k}}{\mathrm{m}}} \approx 27 \text{ Hz} \qquad (4)$$

Therefore, Theoretical $\mathrm{F_t}$ is crossing the threshold value of natural frequency. Hence, $\mathrm{f_p} < \mathrm{f_t}$ (resonance state) which means the crack occurred. This theoretical verification is done for further experimental evaluation purpose.

3.3 Experimental validation

In the previous section, we calculated optimal values using technical formulas for experimental work.

3.3.1 Development of Working Process - CHMS

To design CHMS, it is required to know about the input value that needs to be given to the controller. Here the input value is stress & Vibration, to design the working process it is required to know about the optimal value achieved by the computational technique as shown in figure 7. The threshold values were obtained from FEA and Modal analysis by using a computational tool with Ansys WorkBench. The system includes an Arduino microcontroller, which is used to process the signals from the sensors and determine if there is a problem with the chassis. This Arduino controller is used to control the data from sensors and monitor the chassis based on the input. Overall, the system appears to be a simple and effective way to monitor the health of a vehicle's chassis.

3.3.2 Proto–Model Experimental Validation

In Figure 8, we designed a CHMS with Arduino, Flux sensor, Force sensor, and RGB LED light for demonstration purposes This experiment work is for validation purposes. Both experimental and analytical work are constrained in detecting failures with a systematic approach. With these restored parametric values, the system is to help predict and alert.

Table 3. Natural Frequencies

Mode	Frequency (Hz)
1	37.006
2	47.484
3	64.401
4	105.25
5	144.66
6	164.83

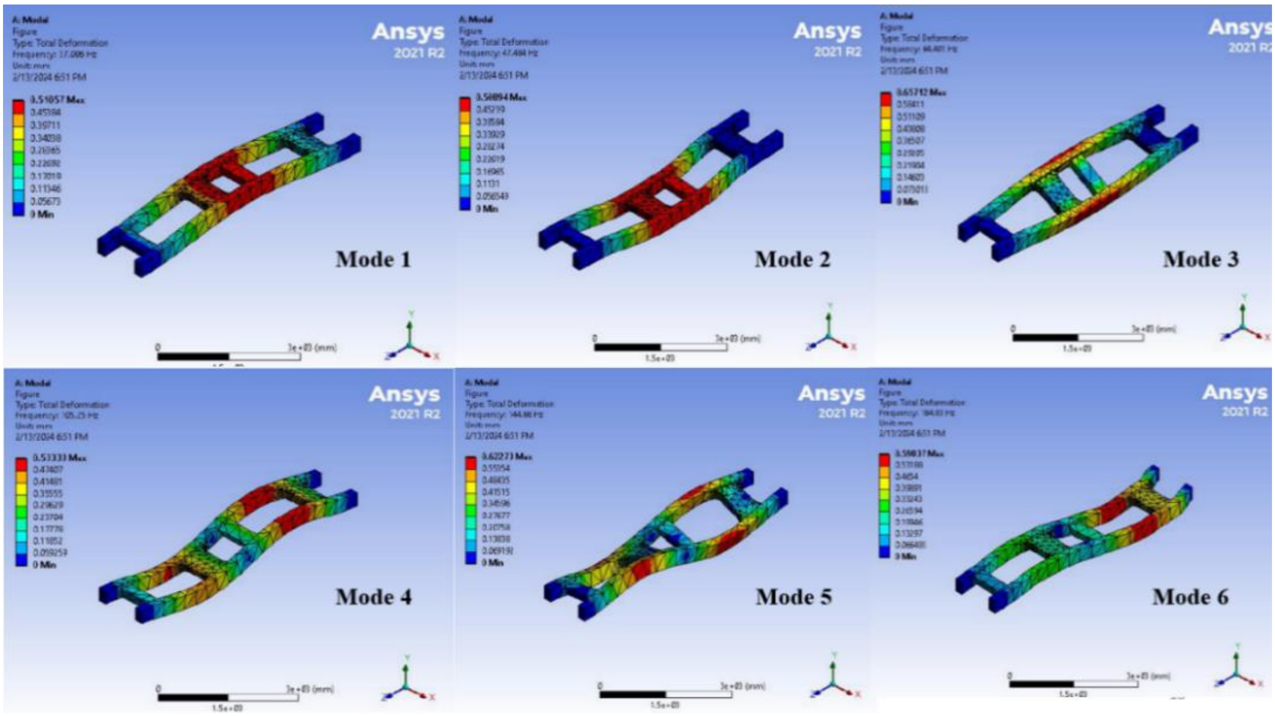

Figure 6. Modal Analysis of Chassis

Table 4. Natural Frequency (Vibration) in the critical area

S. No		Location	Hz
1		At Position 1	104.5
2	**Natural Frequency**	At Position 2	99.89
3		At Position 3	100
4		At Position 4	103

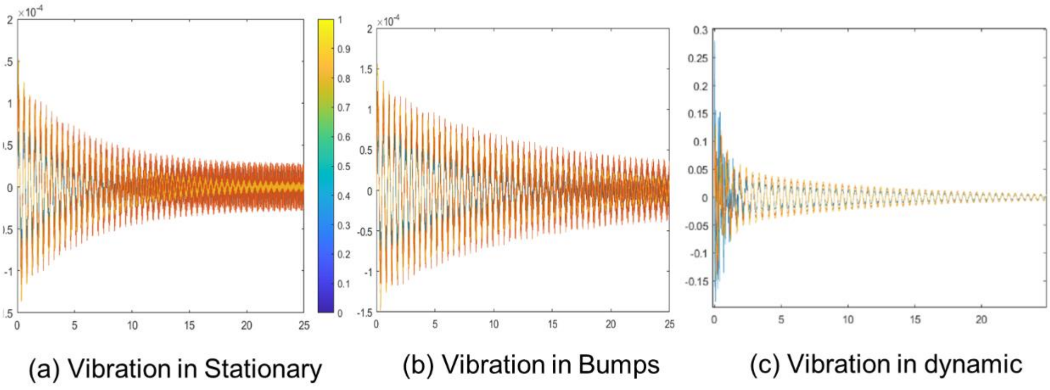

Figure 7. Frequency Graphs: Time-Displacement interval

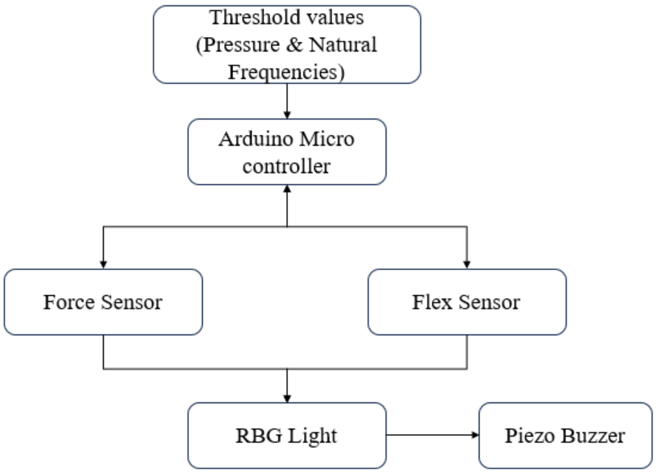

Figure 8. Working principle of CHMS

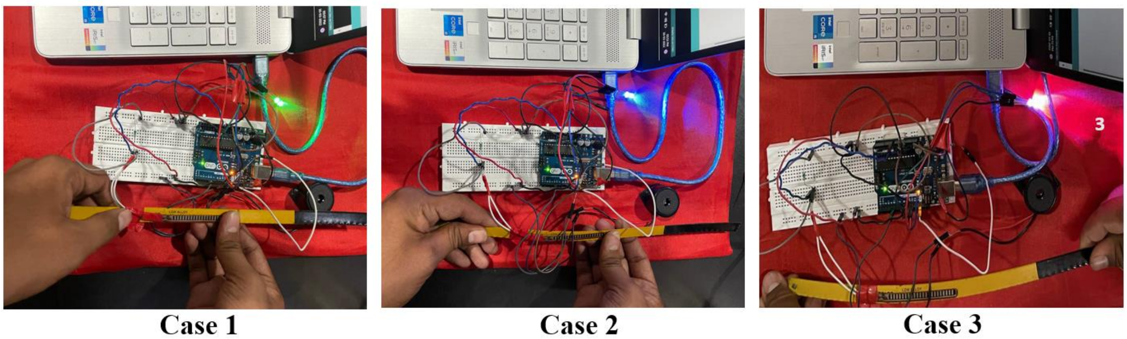

Figure 9. Experimental Proto–Model Validation CHMS 3 Different cases

Case 1:

When the deformation and bending occur at that range between 3 to 5 mm and less than 10° it is in the safe zone.

Case 2:

When the deformation and bending occur at that range between 5 to 15 mm and less than 15° it is in the neutral zone.

Case 3:

When the deformation and bending occur at that range of more than 15 mm and more than 15° it is in the danger zone and the buzzer will alert the user.

The CHMS experiment used data from Ansys Workbench and MATLAB as a benchmark. The maximum level of parameters (Stress Eq.1 & Natural frequency Eq.2) was obtained, enabling the creation of a CHMS module that analyzes and warns of potential vehicle damage.

3.4 Chassis Health: IoT & FEA Co-Relations

FEA and CHMS inform each other in material selection, vibration, and structural analysis, optimal value, sensor placement, predictive maintenance, real-world data validation, operating condition insight, and early detection and prevention as it is shown in Figure 8.

FEA informs CHMS development:

- Material Selection
- Vibration and Static Structural Analysis
- Obtaining Optimal value in critical points of chassis
- Sensor placement
- Predictive maintenance

CHMS Informs FEA:

- Real-world Data validation
- Operating Condition insight
- Early Detection and Prevention

The combined implementation of FEA and IoT in off-highway vehicles has shown in Figure. 9 significant reductions in frame crack incidence, early detection rates, predictive analysis accuracy, maintenance cost, and downtime reduction.

4. Conclusion

In the present work, a ladder-type chassis frame from Cargo Shacman Truck was designed using SolidWorks and Analyzed using Ansys Workbench and MATLAB software. From the results, the obtained threshold value from the computational method will safeguard the chassis through combining the IoT implementation i.e., a Health Monitoring system that predicts and alerts the chassis. With the help of computational tools, it effectively helps to develop the working process proto-model of CHMS. By demonstration of the Proto-model, explains that when the chassis gets deflected 5 mm to 15 mm and bends 15° with a natural frequency of 104 Hz it triggers the buzzer and RGB alert the end user. Finite Element Analysis is effectively utilized for addressing the conceptualization and formulation of the design stages. This paper concluded with Challenges of data integration, sensor selection and process, computational cost, and security and privacy. Overall, the CHMS focuses on future Recommendations for off-highway vehicles including advanced sensor integration, machine learning, material science optimization, and field testing to mitigate frame cracks, improve fatigue resistance, and validate existing designs.

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Authors Contribution Statement

RV: Design Chassis, Analysis & Calculations, Conceptualization, Drafting. RM: Arduino Programmer, Validation, Methodology, Visualization, Circuit designer. PS: reviewing, MK: editing & reviewing, Project administration, Roles/Writing draft. RS: Resources, Literature survey, Circuit designer.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript

Competing Interests

The Authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The experimental values obtained from this experimental work, as well as the computational work of the current investigation, are available from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes