I2 Report

Structural Health Monitoring Validation of a Military Based Vehicle by Computational and Experimental Means

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4th year MEng Group Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed................................ATA AGANOGLU..

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Abstract

This paper provides an overview of Structural Health Monitoring validation. Modal and fatigue analysis are chosen as the SHM methods which aligns with the group project's aim. The analyses are applied onto a sample and the results of the experimental and computational data are used to validate the methods.

The study begins with recognizing SHM as an important area of research and identifies the use of computational means in SHM. The requirement to validate the SHM methods and FEA is also demonstrated. Research on verification and validation in Structural Health Monitoring and information on damage detection levels is provided. According to the requirements of military and rail-maintenance vehicles, a sample is chosen. Experimental modal and fatigue analyses are performed on this sample. Finite Element models to replicate the experiments are developed. Verification of these models are carried out through the analyses.

The comparison between the experimental and computational results is made and analysed critically to identify similarities between these data sets. Modal and fatigue properties are evaluated and the behaviour of the simulations are made to replicate realistic conditions. The SHM methods are therefore validated which proves the potential of FEA in SHM applications. Then damage locations and life cycle of the sample are predicted.

Keywords: Structural Health Monitoring, Validation, FEA, Modal analysis, Fatigue Analysis

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1. Introduction and background

Since its earliest days, human kind has relied upon the machines and structures that ensured the prosperity of society and industry. These appliances have always been exposed to external forces and environmental conditions resulting in deterioration and eventually the failure of the structure. In order to ensure the safe use of these systems, methods that aim to determine and analyse the damage were introduced. Collectively these methods are called Structural Health Monitoring (SHM). the scientific community is striving to automate these systems by implementing algorithms that embed damage detection into structural monitoring. (Lynch, 2006)

Structural Health Monitoring focuses on detecting damage as early as possible. This is imperative for many industries because an unidentified flaw ın a structure can lead to catastrophes. Significant financial loss is standard but consequences can be as severe as loss of human life on an unconscionable scale.

There have been many such tragedies caused by structural failures. This is exemplified in the aviation industry by disasters where an aircraft's wing becomes separated from the fuselage, causing the aeroplane to begin to spiral and crash. The cause for the separation is generally the failure of the lower wing bracket due to fatigue cracking which can be challenging to detect without thorough investigation (Katz, 2007). Another major area for failures due to SHM neglection are bridge collapses because the structures are subject to external forces like weather or pollution. Last year, a bridge collapsed in Rome and caused 43 casualties. The bridge was nearly 40 years old and the poor maintenance of the structure was the reason for failure (Pianigiani, 2018). This indicates the two main elements for structural collapse; failure to identify the cause before the collapse and failure to carry out repairs. Since identification before the disaster is more important, SHM in any industry is vital. Structural failures will continue to take place if correct SHM techniques are not in use.

These events highlight SHM's significance for the reason that they forced industries to set standards in their monitoring and safety evaluation. The experimental methods for SHM used to employ only localized methods such as thermal field, current, radiography, magnet field and acoustic. These damage detection techniques could only identify the damage either on or very close to the surface of the structure however, with the development of new techniques, the analysis of the vibrational changes over the structure has become available. (Doebling *et al.*, 1996)

The improvement of SHM techniques and the demand for global damage detection have resulted in utilizing the dynamic properties of structures. These properties are derived from the applications of physical properties such as mass, damping and stiffness which then are used to identify the changes in modal parameters. Reduction or changes in stiffness due to external forces on the system affect these parameters and causes a visible transition which can be detected by some apparatus. These detections are plotted over time and compared against the base values, vibration signatures, etc. Hence, the SHM technique can be simplified to a pattern seeking system. (S. W. Doebling C. R. Farrar M. B. Prime, 1998) SHM processes are grouped into four categories:

- Operational Evaluation,
- Data Acquisition, Fusion and Cleansing
- Feature Extraction and Information Condensation
- Statistical Model Development for Feature Discrimination (Sohn *et al.*, 2001)

Operational evaluation analyses the external factors, boundary conditions, limitations and quantification of the damage. It is more relevant if the SHM is practised in the field rather than just SHM tests being performed in a laboratory. Data acquisition includes sensor selection, location and number of data points. The conclusions regarding the normalization of the procedures and the data are also made in this part (Sohn *et al.*, 2002). Then the data obtained by the sensors is analysed by using filtering and decimation, commonly with the benefit of Artificial Intelligence. Feature extraction distinguishes the damaged and undamaged segments, mostly executed by evaluating linear modal properties such as the resonant frequencies, mode shapes and flexibility. With technical advancements and adaptation of finite element methods, non-linear and time varying damage interpretations are also being implemented (Valente and Spina, 1997). Statistical models can be developed to improve the SHM processes if data from both undamaged and damaged structure is present. Supervised and unsupervised algorithms are employed to analyse the regression, discriminants and control charts; however, the development of these algorithms require immense amounts of reliable data. Moreover, many of the damage detection methods could only be applied to scaled models and specimen that are taken from the structure which indicates the requirement to validate the performance of these methods in real life conditions (Sohn *et al.*, 2001).

The aim of this report is to evaluate two methods that verify and validate the SHM vehicle models and apply these methods on a sample that exists on both military and rail-based vehicles. The report mainly concentrates on the verification and validation of one sample but the suggested methods are not limited to the use of this particular specimen as these methods can be applied on the said vehicles to validate SHM on full vehicles. So, rail maintenance machines produced by Quattro were also considered for this project. Structural damage identifying data was highly limited which prompted the assessment of the vehicle by the help of creating a physics-based finite element model. Modal and fatigue assessment were applied to a sample to validate the methods and the results of this study because verification and validation (V&V) of the finite element analyses is crucial step.

In the recent years, the adaptation of finite element analysis (FEA) improved the SHM techniques by enabling the development of linear and nonlinear systems detection (Doebling *et al.*, 1996). This advancement together with the implication of modal analysis broadened the applications of SHM on structures with different requirements. FEA is a now a practise that is commonly used in nearly every step of SHM processes, because comparing the SHM results with Finite Element Analysis validates the SHM practise results (Yuan, Ren and Li, 2017). Hence, accurate FEA is significant for correct design of the SHM systems so, verification and validation of the FEA model is required.

Model verification and validation are substantial in any applications involving FEA because critical decisions that concern various stakeholders are made depending on the FEA results. In the model development process, V&V is carried out by checking the models intended use and acceptable range of accuracy. The verification ensures the simulation and the model to have the right implementation whereas the validation investigates the accuracy and consistency of the model through its intended applications. Various boundary conditions are added to substantiate the models application domain and check if the model satisfies the set of conditions set by the requirements (Sargent, 2013). These conditions are important because they define the purpose of the created model which could satisfy several conditions but, this would not mean that the model would have the application domain valid in every case. Therefore, specific models are created in order to appease a set of definitive conditions which increases the cost of the V&V processes.

1.1. Verification and Validation

Finite element model is a tool to construct an ideal mathematical model of the physical structure to analyse the structural behaviour. FEA regulates this model to determine the characteristics of the structure and to compute analyses such as the internal load and mass distribution which could be challenging to the calculate in real life conditions. There are many special FEA software available for these kinds of analyses and one of the most widely adopted software is ANSYS. In SHM, software like ANSYS is mostly employed to perform:

- Strength and deformation analyses
- Modal, transient, steady state, buckling analysis
- Failure, fatigue analysis
- Thermal analysis (*ANSYS*, 2019)

These analyses are critical, and they must be verified to make the results of SHM reliable. Also established by law in aviation industry, a well-defined analysis technique is not adequate to guarantee the validity. Therefore, the data and the model must be certified while considering the presumptions made for the model (Safarian, 2015).

The FEA V&V is therefore essential for the SHM applications. A background on SHM and the use of V&V together with modal analysis in SHM applications are discussed in the next section of this report.

2. Literature review

SHM is a pattern recognition-based technique which aims to detect damage on structures. Even though SHM was not established as scientific research field till late 19th century, many quantitative and non-continuous methods are known to be used. One example that can be given is the train operators hitting the train wheels with a hammer to check if the wheels were damaged (Dawson, 1976). This exemplifies the early use of vibration monitoring, which has been a commonly adopted method for rating performance for decades including the assessment of human body. With the advances in sensor technology, SHM has become a major area of research which resulted in the broadening of SHM types and techniques to evaluate the performance of structures.

The types of SHM are grouped into four broad categories:

- Machine condition monitoring
- Global monitoring of large structures
- Large area monitoring for localised damage
- Local damage detection (Cawley, 2018)

Machine condition is mostly concerned about rotating machines rather than SHM and it is the most common method in the industry. One example to this type of SHM is the Bently Nevadas flagship software developed by Baker Hughes, a General Electric company. This SHM system collects data from the machinery by sensors, portable devices and transfers this data securely into the software platform. The software proactively monitors to detect changes in the system and it can provide three maintenance strategies, run-to-break, time based preventive maintenance and condition monitoring (*Bently Nevada*, 2019).

On the other hand, global monitoring focuses on structural damage detection by a small number of measurements which requires the resonance frequencies of the whole structure. This type of SHM is more relevant for the chosen type of vehicles as a sample is designated. Therefore, more examples are given on this topic.

The first application of global monitoring traces back to detecting damage in off-shore oil platforms in the North Sea. The vibration measurements were taken just above the water line to assess the integrity of the structure by analysing the resonance frequencies as a reaction to waves (Farrar and Worden, 2007).

Another example for global monitoring is the SHM applied to a pier, where the vibration monitoring was carried out by detecting the stiffness changes induced by localised damage. However, in this study it was found that the lower structure was exposed to external changes in boundary conditions such as the mass distribution and temperature. This prompted false alerts for structural failure because the changes in stiffness due to external factors were much greater than the changes induced by crack deformation (Farrar and Jauregui, 1998). The mode shape calculations were double differentiated to rectify the effect of external factors. Also, the study proved that the correct damage detection was possible if an adequate number of measurements along all the members of structure were collected. This method will be considered while performing analyses on the model.

Monitoring for localised damage engages in detecting smaller deformation sizes because it is generally utilized for detecting critical cracks that can lead to catastrophic failures. Specifically, industries that operate with high pressures such as the aviation and oil and gas apprehend the fact that even the smallest crack could prompt a loss of pressure. For monitoring localised damage, the Society of Automotive Engineers released a set of standards to be followed when a crack is detected on the structure. Thermal and visual imaging were also used where vibrational measurements were not sensitive enough to detect some defects such as corrosion. Then the damage is analysed by means of the detectability, size, residual strength and likeliness of the next occurrence (SAE International, 2013) .

In cases where vibration monitoring is not adequate to make reliable detections, localised damage monitoring employs a different technique, guided wave monitoring. This method excites only one of the waveforms out many that propagate along a structure and it outrivals other methods in one directional structures such as pipes. The low frequency use makes this SHM method makes particularly successful for steel structures due to low deprecation of the frequency. The sensors on long structures are generally a part of echo-pulse system. However, the ability to cover most of the structure by single sensor system hinders the accuracy of the measurements and other localised damage monitoring must be used as complementary systems. (Cawley, Lowe and Alleyne, 2003)

Just like every damage on structures, corrosion also produces a reflection on measured signals. Other elements like the alignment of the sensor systems together with external factors introduce a coherent noise in the measurements which cannot be eliminated by averaging (Cawley, Cegla and Stone, 2013). This undesirable noise is limited by industry standards for applying the sensors, but it was found that placing permanent sensors provides more reliable damage classification as it provides a baseline data for prospective measures (Croxford, Wilcox and Drinkwater, 2007). The presence of the noise will be discussed in the experimental validation section.

2.1. Finite Element Analysis in SHM

The examples mentioned in this chapter demonstrate the use of some SHM systems. By globalized and localised methods, SHM applications are designed to detect damage which is rated by the level of detection. These levels are classified as:

1. Structural integrity
2. Damage localization
3. Damage quantification
4. Prognosis of remaining service life (Rytter, 1993)

The levels indicate the ascending level of detection where the first level is to determine the presence of any damage. The damage causes changes in stiffness which decreases the natural frequencies and this change can be triangulated back to the damage location. By analysing the modal damping, the point of frequency diffusion can be found with limited measurements. Integration of FEA benefits the analysis of mode shapes because it allows performing numerical studies without the requirement for executing duplicate experiments. It also enables the cooperation between the model and experimental results. Damage detection, localization and quantification are all methods supported by FEA whereas calculating the remaining life service is a further analysis combining the results from all first three categories (Lopes and Ribeiro, 2012).

Numerical and finite element simulations have become a fundamental part of SHM. They are used for analysing the structures, improving the sensitivity of SHM techniques, calculating and comparing modal shapes, identifying the load distribution, calculating stress concentration factors, performing explicit dynamics analyses, determining changes for the optimal structure shape, etc. This list is not exhaustive (Safarian, 2015). FEA becomes even more significant for SHM with limited measurements. Since this type of SHM is more relevant to the report, only the cases illustrating the handling of FEA in this field are given in this part.

FEA of complex structures are developed to assess the integrity and weak points of the structure. The dynamic and static response of the structure is measured through simulations. This technique is called Structural Identification (St-Id) in the industry and in this study it corresponds to the creation of the reliable estimate model (Catbas, Kijewski-Correa and Aktan, 2013).

Numerical simulations taken from FEA also assist in identifying the depth of the damage. Therefore, they are beneficial in suggesting changes in the design and types of sensors to be used in the damage detection. A study examining damage identification through the mode curvature found that electrical strain gages was a better option for measuring the curvature as they provided direct evaluation of the natural frequency modes (Change, Tomlinson and Worden, 1994). This technique will be considered for the experiments to validate the sample chosen from military based and Quattro vehicles.

After simulating the required tests such as modal and fatigue tests with finite element software, FEA can determine the localised damage and the damage growth. Comparing the experimental results with FEA gives insight into both sensitivity and reliability of the sensor readings. Moreover, the results can be used to form a database to train a damage detecting algorithm (San Millán, Frövel and González, 2015) which aligns with the group project’s aim.

Therefore, FEA accuracy is critical SHM systems. FEA and simulations must be validated before they can be accepted as valid analyses (Safarian, 2015).

2.2. Verification and Validation in SHM

SHM heavily relies on FEA applications to forecast the nature of the structure under certain circumstances. A model is created by utilizing a simulation software. This software transforms the theory behind the natural framework of interaction into mathematical models as a result of mathematical interpretations. The final construct includes the collection of assumptions, constraints and boundary conditions which define the way that the model is evaluated. However, it still may not be possible to predict the model's behaviour accurately in reality because of nature's uniqueness and uncertainty. Hence, the finite element model may not correspond perfectly to the defined restraints in the simulation. (Babuska and Oden, 2004)

In order to confirm the validity of FEA, verification and validation (V&V) must be performed at every step that incorporates FEA. Therefore, V&V techniques are integrated into the development of the SHM and FEA model. A plan for V&V is beneficial and these steps are simplified as:

- Create the model with appropriate dimensions, materials, joints
- Choose the analysis type accordingly
- Design the model elements with precise geometry, mesh size, load and boundary conditions
- Evaluate the model by comparing calculations, reaction forces, deformations, strain
- Validate the results with comparisons, test data, correlation, deviations. (Safarian, 2015)

These steps indicate the standard to develop an acceptable finite element model which will be followed throughout this study. Proof of structure and analyses are also required to comply with these standards. Methods for V&V will be given in more detailed in the theoretical background section.

Apart from constructing a satisfactory FEA, literature on FEA validation illustrates various methods undertaken by different studies to verify SHM systems and FEA.

A Bayesian approach used for choosing the optimal sensor placing also suggested investigating the FEA by scrutinizing the answers of some vital questions. These questions were about the failure modes, responses, probability of damage and FEAs decision-making system (Todd and Flynn, 2011).

A common technique for validating FEA is to compare the results with experimental sensor readings, both during and after the tests. Yet, the accuracy of comparison relies upon the assessment of uncertainty in the results (Yagmur and Bağli, 2009). The comparison is then used for creating a modal assurance criterion which is a statistical indicator of the differences between the simulated and the experimental results. This is often done prior to comparing different analysis results like fatigue testing, transient structural or free vibration. These techniques relate to the general guidelines of developing the FEA and they will be used in chosen sample's assessment and validation.

Another FEA validation method is to analyse fatigue to test structures according to the alterations in external factors. The repeatability of these conditions and necessity to limit the uncertainty in measurements are highlighted by the industry (Farrar, Doebling and Nix, 2001). This technique employs fatigue analysis to compute the zero mean stress and tensile axial stress where reliable results can be derived. Then comparing the experimental and theoretical strength or life cycles of the samples ensure the safety of these systems (TWI, 2018). Validation of fatigue will also be used in the analysis. More details on how to conduct these tests are given in the next section.

3. Methodology

As discussed in the literature review, this report focuses on SHM methods validation by conducting a study on a sample that is inspired by military and rail maintenance vehicles. The aims include assessing the structural integrity of sample and to validate the SHM techniques used in the group project by using computational techniques. The literature review mentions the methods to conduct the validation analysis, which is done by preforming modal analysis, transient structural pand harmonic response with a simulation software. In order to validate the methods that will be used to validate the full structures, a sample that has similar properties to both Quatrro and a military based vehicle is used for experimental procedures. So, the methodology to implement the said analysis is described by the following steps :

- Conduct a sample selection
- Perform modal analysis test in the laboratory and a testing system
- Conduct a fatigue experiment by cyclic loading on the sample
- Develop a FE model for the modal analysis of the sample
- Develop a FE model for fatigue analysis of the sample
- Compare the modal properties and fatigue results
- Validate the model, modal and fatigue results and SHM methods

This section also specifies theoretical background necessary to conduct the said analyses and the processes carried out to complete this project. The comparison of the impact testing results determined the requirement for better testing which was done by professional equipment. Methods to perform computational analyses are also given in this section.

3.1. Sample Selection

Figure – 1: Supacat CAD Assembly taken from ATMP specification sheet (SC Group, 2019)

A military based vehicle and its specification sheet were found online. This vehicle is Supacat (Group, 2019) which is shown by Figure 1.

Figure 1 also illustrates the complexity of the Supacat vehicle. If an SHM study was implemented on this vehicle, the validation of the model would require access to the full vehicle. As said in the literature review this would necessitate modal and strain analysis and experimental data from the sensors placed on the structural nodes.

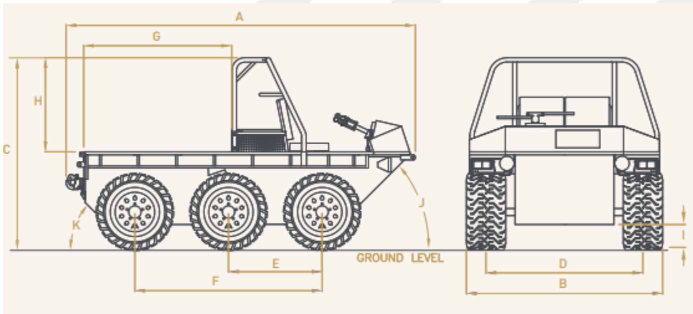


Figure 2 – Technical drawings of Supacat

Figure 2 shows the general technical drawings for the Supacat vehicle without precise dimensions. An outlook on this figure indicates the service of a frontal plate on the exterior. When this design is compared to Quattro rail works machines shown by Figure 3, the use of these kind of plates stands out even more.

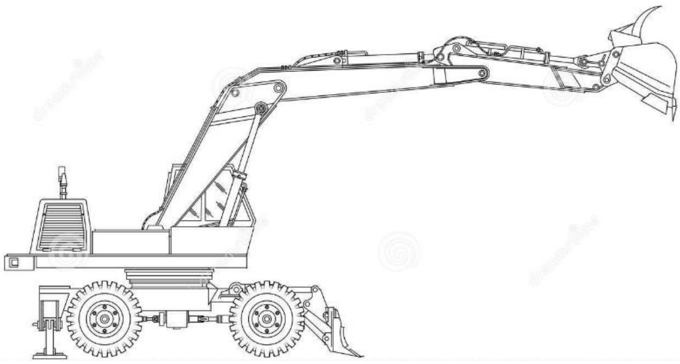


Figure 3 – Excavator Technical Illustration (Galimov, 2018)

An excavator illustration (Galimov, 2018) is presented due to the similarity to the Quattro vehicles which shows the heavy employment of these kinds of plates on arm and body areas. A steel plate with standard dimensions of 100 mm x 50 mm was chosen to certify the common

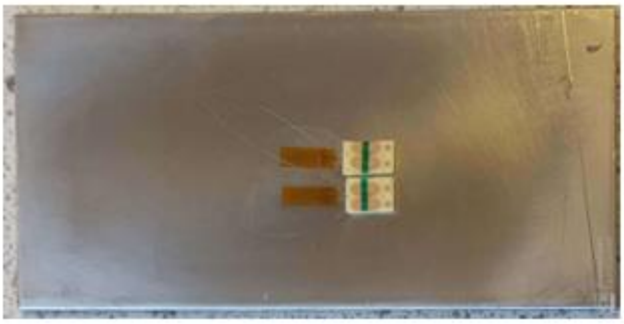


Figure 4 – Sample Base Plate

application in the industry. This is shown by Figure 4 where the plate has strain gauges attached to it for further strain testing. The uniformity of the use and the size of the plate justify the shape of the sample selection. Therefore, verification and validation for a base plate which has been observed to exist on both Supacat and Quattros rail vehicles is chosen for the aim of this report. The validation demonstrates the validation of only one part which will then be used for validating the full structure of the vehicles in the future. The finite element models in this report are also investigated for good engineering practises and acceptability of the results for SHM methods to be used in the project.

3.2. Modal Analysis Theory

Modal analysis can be used to dynamically validate the FE models. The theory behind this analysis is the comparison of the first modes of both real and experimental data set taken from the modes of vibration. As mentioned in the literature review, close correlation of these modal frequencies and assessment of their similarities have been used for validation of FE model validation (Banwell *et al.*, 2012).

Modal analysis basically focuses on the inertial and elastic properties of the structure which gives insight into the limits of the systems response. The resonant frequency where the system can transfer the maximum energy must be found by vibrating the structure to assess the dynamic behaviour. Modes in the structure have modal parameters which depend on properties like mass (m), damping (c) and stiffness (k). The boundary conditions also affect mode shapes so, degrees of the freedom of the system must be considered. From Newton's second law of motion, a system with a single degree of freedom is represented with the following equation

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \quad (1)$$

where x(t) indicates the position of the mass (Ewins, 2000). The sum of external forces acting on the mass also should be balanced with the inertial, viscous damping and restoring forces. Applying Laplace transformation on this equation gives the transfer function

$$H(s) = \frac{1}{ms^2 + cs + k} \quad (2)$$

where the dynamic stiffness is the denominator. The roots indicate the poles of the system. Natural frequency of the system is $\omega_n = \sqrt{k/m}$ and the damping ratio is $\zeta = c/2m\omega_n$ which means that if damping is zero, the poles become imaginary, the transfer function goes to infinity, hence the system would be unstable.

Exemplified by equation 1, several second order non homogenous differential equations can be used to represent systems with multiple degrees of freedom. In MDOF systems, the mass, stiffness and damping contain matrices which yields the following transfer function

$$H(s) = \frac{adj(Ms^2+Cs+K)}{\det(Ms^2+Cs+K)} \tag{3}$$

where the denominator is the characteristic polynomial with the roots of conjugate pole pairs for number of modes of the system. Equation 3 can be rewritten with pole residue form.

$$H(s) = \sum_{m=1}^{N_m} \frac{R_m}{s-\lambda_m} + \frac{R_m^*}{s-\lambda_m^*} \qquad R_m = \psi^m \psi_m^T \tag{4}$$

Rm indicates the residue matrices where Ψ_m is the vector of the mode shape m. So, equation 4 proves that a system with N number of DOFs can be written as the sum of the SDOFs which have Ψ_m shape vectors where m=1,…,Nm. (Guillaume, 2012).

These equations define the theory behind the modal analysis where detection is achieved with accelerometers and there is a large number of outputs. Therefore, algorithms detect the frequency domain and perform a least squares estimation. The common denominator model describes the relation between the input and the output with a transfer function of

$$\widehat{H_k}(\omega) = \frac{N_k(\omega)}{d(\omega)} \qquad N_k(\omega) = \sum_{j=1}^{n} \Omega_j(\omega) B_{kj} \qquad d(\omega) = \sum_{j=1}^{n} \Omega_j(\omega) A_j \tag{5}$$

where A and B are coefficients to be calculated. The time domain model solution method for function $\Omega_j(\omega)$ also includes the a sampling period of T (Guillaume, 2012). Better estimates are made by using a Jacobian matrix when parameters are linear. The real part of the ($J^H J$) matrix form a Toeplitz structure which can be found by using Fast Fourier Transformations. These equations describe the theory of modal analysis. Two experimental methods were used for administering this investigation.

3.3. Building an Impact Testing System

For the first method, in order to measure the natural frequencies of the sample, an accelerometer was purchased, and a testing equipment was built. The main driving factor to build a portable detection testing system also aligned with the group project's aim which was to establish a fast and effective SHM method to detect damage in real time.

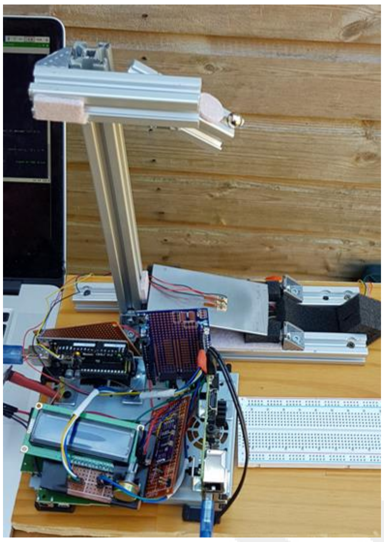


Figure 5 – Impact Test Set-up

An ADXL345 triaxis accelerometer (Adafruit, 2019) was purchased and attached onto the sample by a super adhesive according to the specification sheet for the sensor.
Rectangular steel frame parts were used for constructing a ramp which was secured onto a wooden panel. A trigger mechanism was added to this ramp and a steel ball was anchored by a trigger mechanism that was set at the end of this ramp. This mechanism ensured that the drop of the impact test flowed the testing standards and same drop was repeatable for all tests.

The sample plated was settled on rigid foam which was also secured by felt placed on to the frame. A data capturing program was created by integrating the Arduino and Python libraries which will be explained further in the Section 3.8. The ball was dropped on to the edge of the sample and the resulting frequency response was captured.

This method was later checked for accuracy by laboratory grade equipment and it was found to be not accurate enough to continue with modal analysis. This issue will be addressed in the analysis section.

3.4. Impact Testing by Laboratory Equipment

After building an impact testing method system, the sample was examined by highly sensitive sensors. Accuracy of the data was checked by comparing the measured natural frequencies and it was proven that the highly sensitive sensors were more precise and reliable. The data for this report was then taken by these sensors.

In this experiment, to distinguish the mathematical and physical poles a stabilization program made by DataPhysics was used (DataPhysics, 2018). A hammer test was applied and the method for obtaining the natural frequencies of the sample was performed by the following steps.

- The sample was hung free form by the clamps with elastic bands where no damping was present. As the modal analysis test was done after the fatigue test and considering the sample size, the sample was hung by elastic bands rather than drilling holes into the sample to attach strings.
- The sample was excited with an impact hammer and the excitation was repeated several times to ensure adequate excitation and eliminate rippling effects of the damping caused by the elastic band. A PCB single axis accelerometer was used for measuring the response.
- Accuracy of the accelerometer was also crucial as any soft material used for attaching the accelerometer could affect the high frequency transmissibility. Since PCB made sensor was used for the testing, the PCB petro wax was applied onto the accelerometer to mount it onto the sample. This eliminated possible noise cause by the testing environment (Piezotronics, 2019).
- The sample was analysed by using a SignalCalc Ace by Data Physics which has realtime analysis capability. The Data Physics program provided the FFT spectrum analysis to identify the preeminent frequencies of different mode shapes.

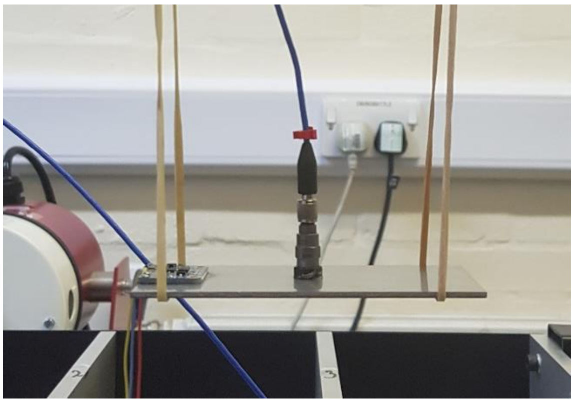


Figure 6 – Hammer Test Set-up

All frequencies were excited and amplitudes of the frequency response function were recorded.

The figure above shows the experimental set-up conditions for the sample which was levelled with elastic bands. Possible interference of this elastic band on the results will be discussed in the analysis section. The results of this experiment can be used for calibrating and validating future FE models.

The equipment for this experiment was already made available by the university, so did not incur any costs. Therefore, TRAC assessment was not included in this report.

3.5. Modal Analysis by FEA

FEA technique implementing modal analysis also uses the same principles. The free vibration determines the mode shapes and the corresponding natural frequencies. Therefore, the modal analysis transforms into an eigen value problem for the stiffness and mass matrices. Equation 1 represents the eigen value problem of a spring mass system motion for FEA modal analyses.

The general solution for equation 1 is given for the mathematical model. However, in vibrational modal analysis the damping is ignored which gives the shapes of most dominant deflections with unspecified loading conditions (Bathe, 1996). Equation 1 without the damping can be written as the following equation.

$$[M][\ddot{U}] + [K][U] = [0] \tag{6}$$

Corresponding to equation 1, the eigen values indicate the frequency and the eigen modes complementing these frequencies are represented by deformed shapes of U. Therefore, equation 6 shows the eigensystem utilized in finite element applications. The goal is to solve for U and find the eigen values which are the set of scalar factors to the linear equation.

In order to find the free vibration throughout the structure, harmonic motion is evaluated at all nodes and [Ü] is amounted to $\lambda[U]$ where eigenvalue is shown by λ (Stratan, 2018). So, the equation that only incorporates mass stiffness can be written as below.

$$[M][U]\lambda + [K][U] = [0] \tag{7}$$

However, this equation is significant because it shows the independent nature of the modal analysis deformations to the ones made in static structural mode in ANSYS software. There is no real load applied in modal analysis, the deformations are simulated with respect to the stiffer parts within the structure. This concludes that modal analysis is used for only obtaining the mode shapes and the frequencies.

Also, this equation can be scaled by multiplying U with any real numbers because if the eigen values are found the satisfy the equation 7, then any scaling factor can be implemented on this equation. This again relates back to the insignificancy of the deformations in modal analysis as the amplitude of the deformation is unimportant. Hence, the shapes of the modes can be scaled with choosing a relative maximum displacement over the structure (infinity norm) or Euclidean norm which underscores the need for normalization (Clough and Joseph, 1993).

Modal analysis results were compared with the FEA results and ANSYS software was used for computational study. The methodology to create the FEA is given as below.

- A simple geometry was created in Design Modeler matching the dimension for the sample and the accelerometer. Point masses were defined to represent strain gauges.
- Material properties of the geometry were assigned accordingly.
- Meshing was compiled for the sample by assigning the finest element size available for the ANSYS academic version. The mesh convergence study shown in the analysis section concluded that an element size of 2 mm was adequate to optimize accuracy of the results and cost of computing power.
- Mesh refinement was done at the accelerometer attachment region for better results and accuracy
- Harmonic index range was switched to program controlled.

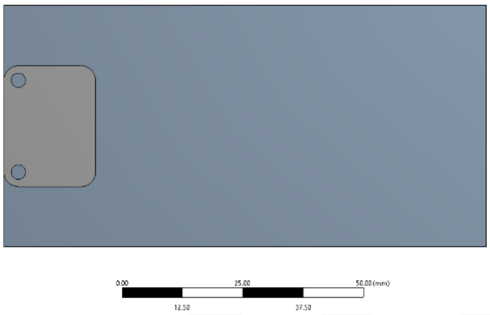


Figure 7 – FE model for the sample with accelerometer attached

The solver was selected to run a modal analysis where no boundary conditions were present. By using the max modes to find command, 15 modes were found for the sample. Mode reuse was selected to allow the subsequent solved points, increasing the efficiency of the analysis. The output was only reviewed for natural frequencies of the modes as the deformed shape of the sample was scaled by an arbitrary factor. Mode shape results were created and natural frequencies for 15 modes were determined.

3.6. Modal Assurance Criterion

Comparison of the modes is a significant step for validation process in modal analysis. One comprehensive method for modal analysis is to use a modal assurance criterion which compares the modes quantitatively. Coherence to the Frequency Response Function (FRF) is computed and linear regression of the least squares estimation (see Section 3.1) is found. This data is then colour coded to indicate the extent of difference between the experimental and FEA results. This table becomes a mass orthogonal matrix which indicates the consistency of the modes. The MAC is calculated by 2 sets of vectors of $\{\varphi_A\}$ and $\{\varphi_X\}$ which are then used to build the said matrix (Pastor, Binda and Harčarik, 2012).

$$MAC(r,q) = \frac{\left|\{\varphi_A\}_r^T\{\varphi_X\}_q\right|^2}{(\{\varphi_A\}_r^T\{\varphi_A\}_r)(\{\varphi_X\}_q^T\{\varphi_X\}_q)} \tag{8}$$

A full MAC was aimed to be achieved as a part of this study, however due to size of the sample and lack of testing equipment only first 3 mode shape frequencies were measured. The frequency of the modes will be compared in the analysis section.

3.7. Fatigue Testing

Fatigue testing is the process of applying cyclic loads onto structures to initiate a localized damage which may result in structural failure. This failure develops in three stages which are the initiation of the crack, crack growth and the fracture. A mechanical fatigue caused by high cycle loading was examined in this report.

The sample that is subjected to a load under its tensile conditions may never reach mechanical failure but if this load is applied a sufficient number of times, the sample starts to fatigue and the load could induce a structural failure. The plot of these high cycle stress vs material life is called an S-N curve also known as Wöhler curve. These curves exist for known materials and they are obtained by applying a regular sinusoidal load on the materials where the number of cycles to failure is recorded (Burhan and Kim, 2018).

Some metals subjected to cyclic loading result in specific stress-strain behaviour. This behaviour is explained by cyclic hardening where the energy diffusion capability of the sample is reduced and it is shown by the flattening curve (Xu *et al.*, 2015).

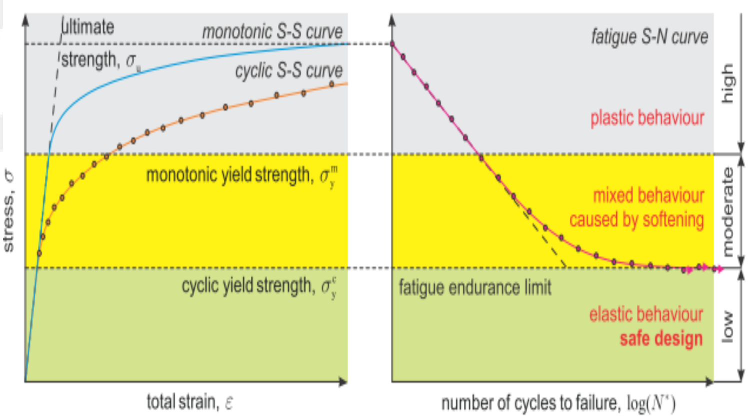


Figure 8 – Cyclic Yield Strength Curve (Gorash and MacKenzie, 2017)

Safe design of steel structures acknowledges this behaviour of structural steel which takes place in initiation, growth and flattening steps. The structures in this behaviour transforms from a non-linear transient form to plastic deformation. Hence, a transient structural analysis was carried out with the simulations.

Fatigue testing to failure has also become an industry standard method to compare experimental and simulation results where the necessary validation can be made. So, the methodology to perform an experimental cyclic loading test on the sample is defined as below.

- In order to perform the experiment a health and safety form was filled. After it was approved by the lab technician and the supervisor, lab induction was completed and the experiment was executed. The form and the details can be found in the project management section of the report.

- The use of electrical strain gauges was identified in the literature review, however, their selection was done by another member of the group. Then, these strain gauges were applied on the sample by an adhesive. The gauge placement was chosen as the centre of the plate where the applied cyclic load could result in the maximum curvature of the sample.
- Instron 8872 servo hydraulic system was used for fatigue loading. The sample was prestressed to limit the samples motion to one direction. The prestress load was found by trial and error method. Then ±150 N was applied onto the sample at 2 Hz rate which is shown by the plot in Figure 9. The motion form was measured by an LVDT displacement transducer.
- The data capturing method that was also mentioned in Section 3.3 was used to record the strain on the sample by the strain gauges. Further information on this system will be given in the next section.

Instead of the strain gauge readings, the data taken by LVDT sensor was utilized as this section of the report intended to validate the sample by comparing the experimental data with the FEA results.

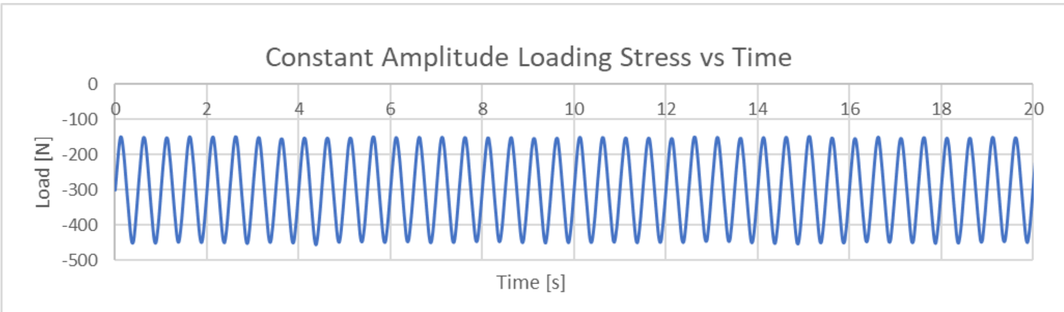


Figure 9 – Cyclic load applied on the sample

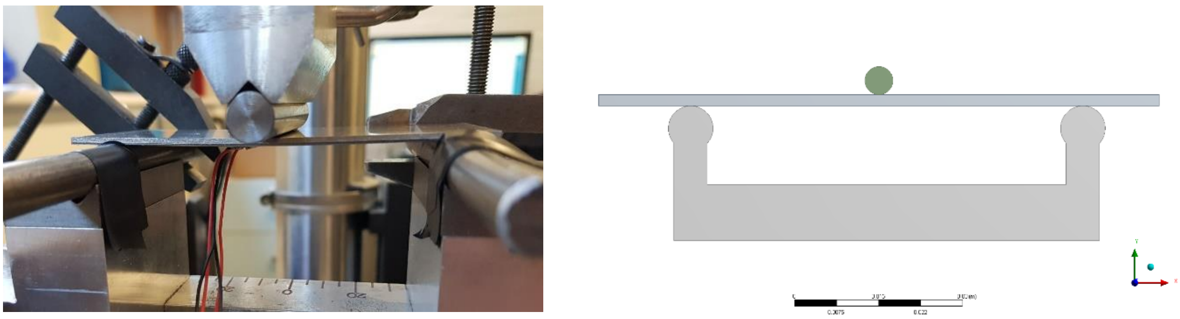


Figure 10 – Testing and computational representation

Also correlating fatigue testing data to FEA results is another FEA validation method. This also provides structural durability development and establishment of confidence in fatigue predictions. Hence, the FE model was prepared by replicating the fatigue test in the ANSYS software (*ANSYS,* 2019). Methodology to create this experiment computationally and analyse for fatigue is described by the following steps.

- The dimensions of both the testing equipment and the sample were measured and a finite element model to represent the testing structure was created according to the exact dimensions in transient structural.
- The sample face was separated into segments to achieve the structural mesh and define the contact types. Contact regions were defined by using imprinting faces feature in the Design Modeler.
- Next, meshing was done by the adaptive feature and the mesh size was given by program controlled. The contact face segments on the sample were given a finer mesh sizing for better investigation in these complex regions. Number of nodes were reviewed and found to be 5130.
- After the meshing, scoping of these contacts were altered. Since the three-point bend required free movement at the edges of the plate, frictionless contact type was chosen for all contact regions. The contact and target bodies were selected to be facing each other. The Pinball region effect was also activated to match the radius of the cylindrical supports and the bending rod.
- Contact types were selected as normal to target method and the interface treatment of these contacts was prescribed with adjust to touch option.
- Automated time stepping was defined in the boundary conditions where substep control was switched on. Initial substep of 50 was found to be both computationally fast and accurate at the same time.
- The step number was set to two due to the motion of the testing equipment which applied the force in the first step and retracted this force in the second step, creating a harmonic motion. Weak spring feature was left for automatic program controlled and large deflection option was switched to on for both load steps to include non-linearity in the analysis. The correct forces and were also marked on the set faces.
- Fixed supports were defined by selecting the faces and constraining them to only one degree of freedom. Hence, deflection in only one direction was allowed.

The analysis was conducted by solving for directional deformations, strain and fatigue where life of the sample was calculated by means of cycles and damage. The force convergence was plotted and time load step convergence time was also found. This indicated that the analysis was successful. The comparison of experimental and FEA results are given in Section 4.8.

3.8. The strain and fatigue reading equipment

The strain and fatigue reading system was created by combining an Arduino Uno board and Raspberry Pi microcontroller. These processors were integrated and data transmission was assured by programs. The creation of the system was done by another group member (Preston, 2019).

The only relevance of this system to this report was the reading of the accelerometer data in the Section 3.3. Also discussed in the section, the natural frequency results obtained by this device were not substantial for this study which is also shown in the analysis section.

The measurements obtained in the Section 3.4 and Section 3.7 were used for comparison to the FEA results.

3.9. FE model Verification and Validation

Finite Element model validation is a process including the creation of the model. Some of the elemental steps necessary in this process were defined in the Section 2.2.

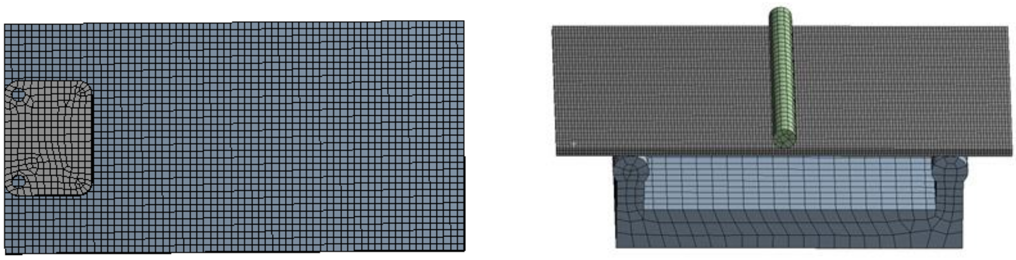


Figure 11 – FE models with their appropriate meshing size

The figure above demonstrates the final models used in this report. For a comprehensive finite element interpretation, the driving factors for the FEA were established. Then the priori mathematical model was converted into the computational model. The mathematical model verifies the FE model and the simulation outcome validates the results (Schlesinger, 1979).

The goals for the creation of the FEA was established earlier in the project. The models were kept as simple as possible. Realistic boundary conditions were defined and loads/excitations in the experiments were identically replicated. The assumptions and limitations of the models were documented. Output for the results were analysed according to the desired solution types by the experiments.

Apart from the aforementioned V&V techniques, there are various ways to validate FE sub models and overall models. The relevant validation methods are presented in the table below and validation analyses are carried out in the next section.

Table 1 – Verification and Validation methods (Sargent, 2013)

Method	**Explanation**
Animation	The FE model is simulated and the model behaviour is observed. The modes of free vibration were noted. In the fatigue testing, The movement of the sample edges were recognized to match this behaviour in FEA.
Comparison to other models	Results of the simulation can be compared to the known results of other models, simulations and analytical models. This part is given by the comparison to the experimental results.
Data relationship correctness	Modal analysis and fatigue data were compared and analyses were made through this comparison. Moreover, the data relationship of the simulation results was checked by providing the sample to another group member (Jeje, 2019) where the interaction of the sample and more parts were examined.
Event validity	Event validity is an extension to the animation section. The substeps of the simulation define the computational calculation steps so the step where the maximum displacement of the sample can be found. This is compared to the experimental data to validate the samples behaviour.
Multistage validation	This is the general validation approach taken in this report. Model is developed through understanding, assumptions are testes and, output relationships are analysed.
Operational graphics	Various performance measures are checked during the simulations. These graphics such as the force convergence, indicates the FEAs performance achievement of a solution and boundary condition correctness which are significant for validating results.
Parameter variability–sensitivity	This defines the relationship between the FE model and real life conditions. The parameters defined in the simulations can lead to crucial changes in the output results. Hence, values like stiffness, damping, fatigue life intensity were ensured to be the identical for each iteration. A mesh convergence study was also performed to optimize the output accuracy and the computational power. In the modal analysis, three modes of vibration

	were found and trends for these frequencies were checked in the simulations.
Predictive validation	This correlates to the last step of this report which is to determine adequate validation of the sample to predict the samples behaviour in real life. The performmce of the sample will be discussed in the next section.

4. Presentation of experimental or analytical results

4.1. *Impact Testing*

The graphs below indicate the response obtained by the accelerometer against an undefined impact. This impact testing aimed to mobilize the testing process and it was mentioned in Section 3.3.

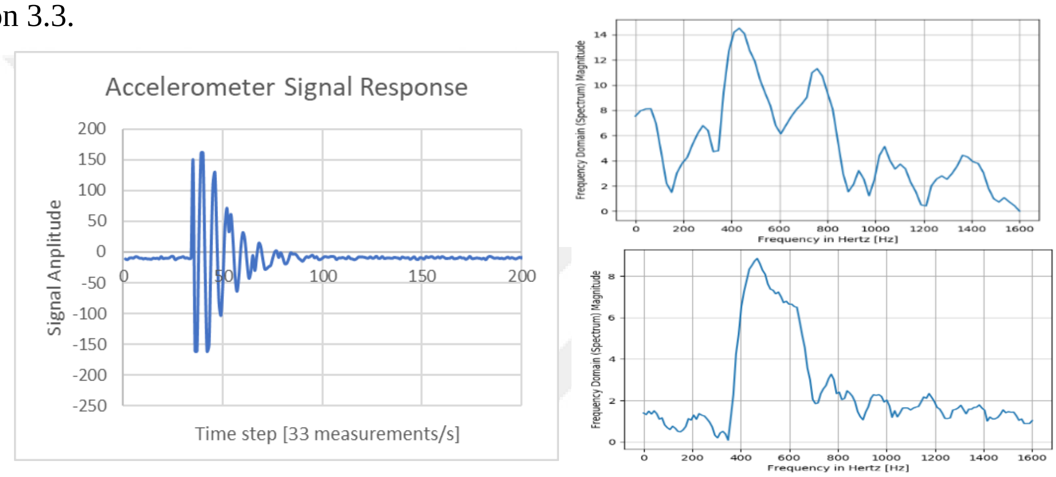


Figure 12 – FFT graphs of impact testing

The response was measured and the FFT formations were executed by writing a Python script which has an integrated module for graph transformations. However, the two plots on the righthand side indicates a double excitation which leads to imprecision. These results were the main reason to request a frequency response function obtained by highly sensitive sensors.

4.2. *FEA Specifications*

The FEA simulations were based on the modal and fatigue experiments. The behaviour of the sample in both simulations were captured. Geometry non-linearity and contact non-linearity were only observed for the fatigue analysis. A mesh convergence study was carried out of the modal analysis through

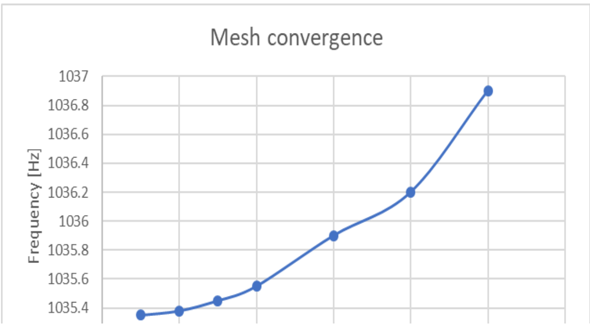


Figure 13 – Modal Analysis Mesh Convergence

FEA. This was accomplished by comparing 6 frequencies given by the same mode with different element sizes. The 2 mm element size was chosen after the mesh converge study shown by Figure 13 and 10237 nodes were found.

Another mesh convergence study was attempted for the fatigue analysis produced by FEA. However due to the complexity of the contact regions, adaptive mesh size was given and it was managed automatically by the ANSYS program. So, a mesh convergence couldn't be completed for the fatigue analysis. The finest mesh size available by the ANSYS academic licence was employed in the simulations, 5130 nodes were defined and mesh quality was checked for errors.

Structural steel was used for both FEA simulations and the table below displays the properties for this material.

Table 2 – Material properties for Structural Steel (*ANSYS*, 2019)

Density	**Young's Modulus**	**Thermal Conductivity**	**Specific Heat**	**Tensile Yield Strength**	**Tensile Ultimate Strength**
7.85e-06 kg/mm³	2e+05 MPa	0.0605 W/mm·°C	4.34e+05 mJ/kg·°C	250 MPa	460 MPa

4.3. *Modes of Vibration frequencies*

```
===== Measurement Parameters =====
Fsamp                  : 12.80kHz
DeltaT                 : 78.13µS
Fspan                  : 5.000kHz
Remove mean of Xx      : Off
DeltaF                 : 781.3mHz
Tspan                  : 1.280 S
BlockSize              : 16384
Spec Lines             : 6400
Trigger                : Input
Session Trig           : Off
Window                 : F/Exp
Average Type           : Stable
#Averages              : 10
Preview Average        : Off
Pacing Mode            : Off
H2 Estimation          : Off
Reciprocal of Hxy      : Off

===== Open Loop Hxy Mapping ======
Method                 : Two Channel
k0                     : 1.000
k1                     : 1.000
X                      : 1
Y                      : 2

========== RPM Parameters ========
RPM Mode               : RPM Off
|
====== Waterfall Parameters ======
WF Records             : 20
WF Stop At Full        : No
```

Three modes of vibration were achieved and each mode's natural frequency was captured by the Data Physics signal processor. The methodology for this experiment was given in the Section 3.4. The FRFs for two samples were obtained by the measurement parameters are shown on the left.

The multivariable operations for frequency domain estimates were calculated by the Data Physics processor. The theory behind this common denominator calculation was acknowledged in Section 3.2. The large amount of imaginary and real parts of the poles were saved to a text file. The plot shown by this figure was obtained by repeating the impact test numerous times until the point of stabilization. The imaginary poles indicated the peaks, resonant frequencies, whereas the real poles demonstrated a tendency to be zero at natural frequencies. However, there is visible noise present in the plots as the real poles vary from zero. The table below indicates the one frequency mesasurement taken from each mode shapes.

Figure 14 – Frequency Response Fuctions of Fatigued and Unfatigued samples

Table 3 – Frequencies for different mode shapes

Frequency	**Mode 1**	**Mode**	**Mode**
Fatigued	1040	2800	4000
Unfatigued	572	2590	3310

It is evident that unfatigued and fatigued frequencies differ from each other. The fatigued sample's frequencies will be compared to the ones obtained by computational modal analysis later in the analysis.

4.4. FE Modal Analysis

This analysis was conducted by following the method explained in the Section 3.5. The first 6 modes of vibration were found to be directional modes which did not result in any changes in the sample formation. The modes from 7 to 15 were found to be bending modes. These bending modes were recorded in a free-free edge simulation. The behaviour of the modes was checked to ensure correlation to real life conditions.

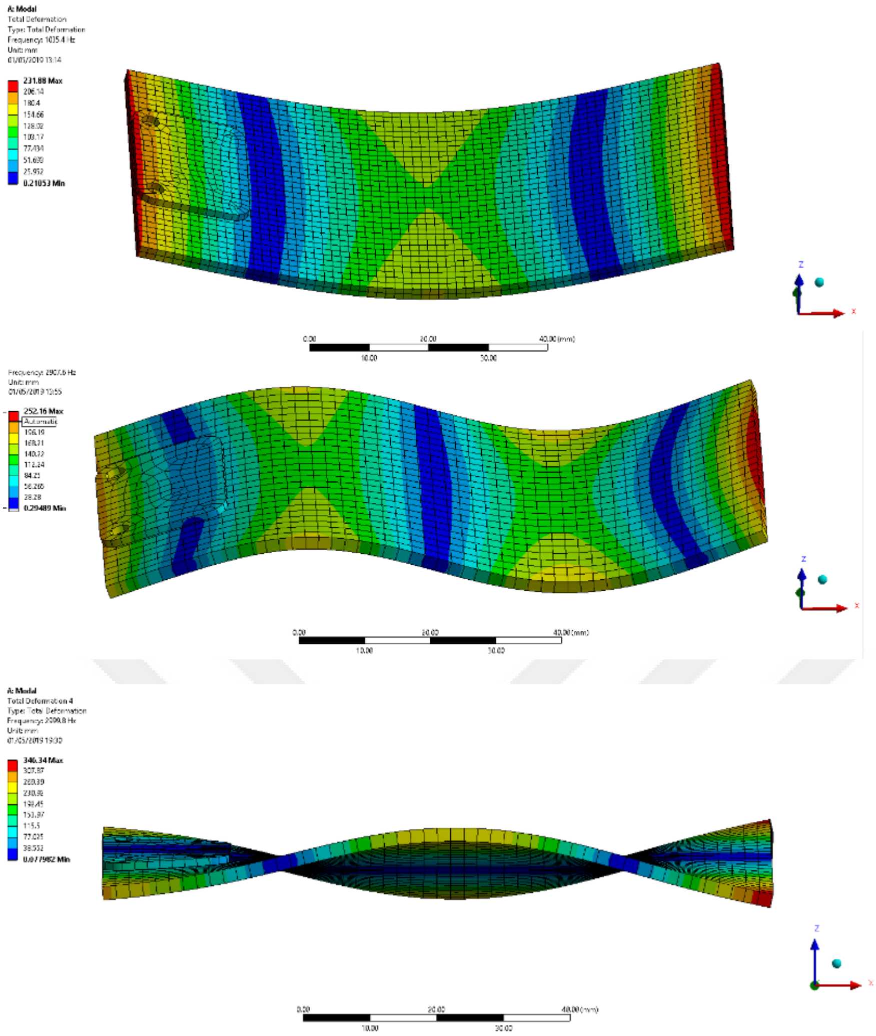


Figure 15 – Illustration of mode shapes for the fatigued sample

The figure on the left-hand side shows different examples of mode shapes obtained by the ANSYS modal analysis.

The corresponding frequencies for these mode shapes are given as below.

Mode	Hz
Mode 1	1035.4
Mode 2	2806.3
Mode 3	4044.6

4.5. Comparison of Modal frequency

The weight of the sample was measured as 78.5 grams and the accelerometer was 3.14 grams by its specification sheet. The first order of resonance measured by the hammer testing was 1040 Hz whereas the computational result was 1035.4 Hz. The error between these results were less than 1% for the first 2 modes. Although, without the accelerometer attachment to the sample, this error was found to be much more significant. This showed that the weight of the sensor and contact type between the accelerometer and the sample had a great effect on the measurements. Table 4 shows further comparison between the experimental and FEA results.

Table 4 – Comparison of Frequencies for modes

Mode No	Test	FEA	Difference
Mode 1	1040	1035.4	*0.44 %*
Mode 2	2800	2806.3	*0.23 %*
Mode 3	4000	4044.6	*1.12 %*

By evaluating these results, it can be stated that the computational modal analysis and experimental hammer testing results have consistency. The deviations could have resulted from the excitement of different mode shapes which will be mentioned in discussion. This concludes the modal analysis validation which was a prerequisite test for further analysis.

4.6. Fatigue Test by Experiments

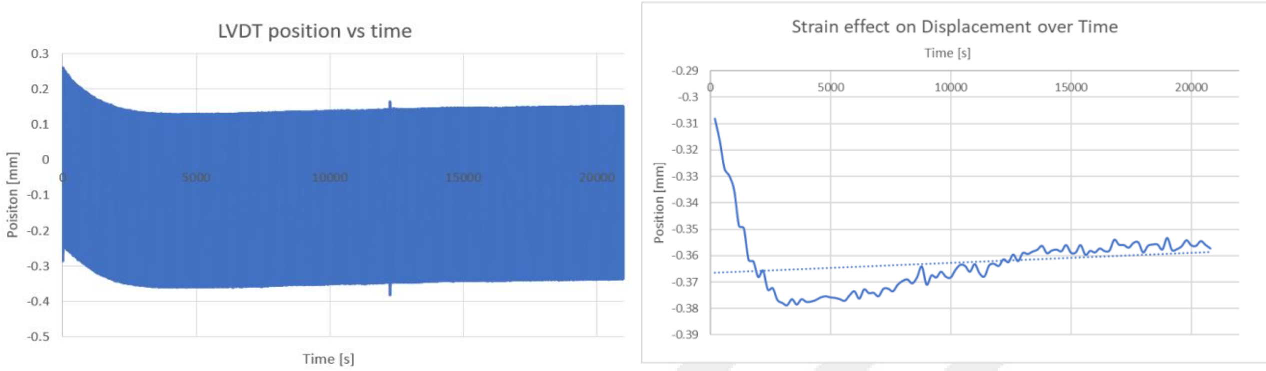


Figure 16 – Plot of Fatigue data results over time

The plots above show the data measured by the LVDT displacement sensor. Under the cyclic loading that is shown in the Section 3.7, the sample plate displayed a 0.288 mm movement in both directions throughout the graph. This value is unchanged for the whole cyclic testing and will be mentioned later for analysis. The strain effect cannot be observed fully as the sample was not tested till fracture due to limitations on the testing resources. A total of 1,200,000 cycles were applied on the sample and at the end of the testing, the sample displacement shifted nearly 0.02 millimetres, proving that fatigue damage was present on the sample. The plot on the right-hand side shows the position of the maximum displacement location of the sample and it substantiates that plate is dissipating less energy gradually, hence bending less. This was concluded to be a result of cyclic hardening which happens in the first downwards curve followed by the displacement gradually reducing.

There was no evident damage but miniscule bending on the sample that could be seen with human eye after the experiment. As the damage could have been in micrometres, further validation of this fatigue effect was requested, however due to the university’s available resources this couldn’t be accomplished. Further validation will be recommended in the future work.

4.7. Fatigue Test by FEA

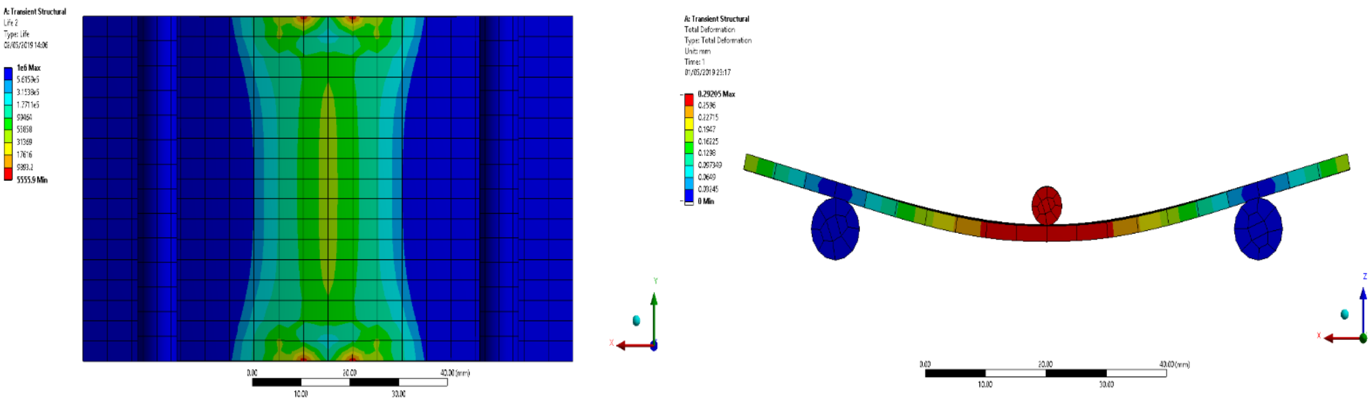


Figure 16 – Computational Fatigue data results

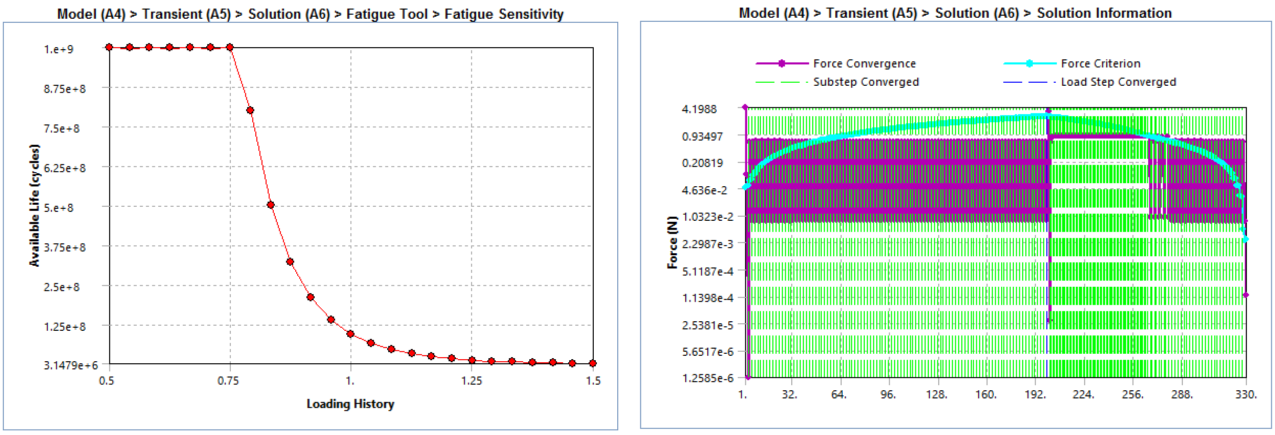


Figure 17 – Fatigue Sensitivity and Force Convergence

Since FEA validation included the creation of the model, the testing conditions were replicated in the simulations. Dimensions, materials, loads and boundary conditions were reproduced and non-linear analysis was performed by Transient Structural. The details regarding the methodology of the simulations can be found in Section 3.7. The base of the sample holder was disregarded because it was not the focus of the study and it blocked the damage locations view.

4.8. Fatigue Results Comparison and Validation

Accurate demonstration of the geometry and conditions were established. The behaviour of the sample was also found to be realistic. After the loading and boundary conditions were paralleled, the displacement results of both methods were compared. When the harmonic force was applied the displacement was found to be 0.288 mm with the experiments and 0.292 mm with the FEA results. This equals to only 1.3% discrepancy between the results and it is a critical element for validating the FEA results because it indicates the similarity between the real life and simulation conditions.

Fatigue data also indicated there was similarity between the fatigue curves and cyclic hardening theory which is supported by the trendline that can be seen in Figure 16. The strain curve obtained by the experiments indicate the initiation point of the gradual decrease of displacement was after around 5200 cycles. The FEA results also indicate this fatigue damage could initiate at around 5555 cycles, indicating a 6.3% deviation. The results therefore show adequate similarity to the experiments and the modal analysis and fatigue methods can be used for validating a full SHM vehicle in the future. The similarity between the results encouraged further predictions for the life cycles available for the sample. In an additional analysis, strain life of the sample was compared to the stress life and strain was found to be a better correlation to the experimental results. FEA results indicated even with the given fatigue, this sample could last minimum 9.75×10^7 cycles without failure. More validation on this topic was suggested. Furthermore, locations vulnerable to damage were identified in Figure 16 which again could be tested and validated in the future.

5. Discussion and conclusions

5.1. Discussion

The aim of this report was to investigate the accuracy of SHM methods. In order to achieve this aim, these methods were applied onto a sample plate which can be found on both military based and rail maintenance vehicles. Modal and fatigue analysis validation on this sample were achieved through experimental and computational methods which indicated that these techniques could be used in the future to validate the full model for these vehicles.

The significance of Structural Health Monitoring was deliberated in the literature review where the SHM methods such as modal analysis and fatigue analysis were mentioned. The use of FEA in these methods were addressed and a general approach for creating a valid FEA to increase the credibility of the results were remarked.

Requirements for having validated methods for structural health monitoring was also recognized in this report. Moreover, from these validation techniques, comparison of experimental and simulations was identified as the focal approach taken for this study.

First step was to choose a sample which was accomplished in Section 3.1. The dimension and shape selection of this sample was also substantiated. This was followed by conducting the impact test by two methods where the laboratory tests were proven to be more accurate and they were chosen as the way forward. Hence, three mode shapes and corresponding natural frequencies were identified by the sensors in the lab. Frequency response functions were plotted by DataPhysics signal processor when real and imaginary poles were obtained. Noise that was sourced by the irregularity of the elastic bands, was detected in these graphs. This could have resulted in differences between in-plane and out-of-plane modes. Then cyclic loading was applied on the sample to execute the fatigue analysis. LVDT sensor was employed to track the displacements of the sample for 1.2 million cycles. The results were recorded and processed by a set of codes developed with Python.

The FE models for modal and fatigue analyses were developed by ANSYS simulation software. As the experiments already had simple geometries, there was no further simplification process implemented for the simulations. The mesh convergence study was done for modal analysis and 2 mm was found to be optimized element size however this couldn't have completed for the fatigue element. Directional displacements, deformations, force reactions and behaviour of the simulations came close to the ones from experiments and the solution performance was monitored by force convergence. The experimental set-ups were adequately correlated to the simulation models. Modal analysis simulation was maximum 1.2% different than the findings of experiments whereas fatigue data demonstrated a 6% deviation. However, the sample was not tested to destruction which indicated requirement for further validation of these results. In order to legitimize the comparisons between data sets, the following elements were verified.

- Material properties
- Geometry of the models
- The representation of coinciding surfaces and contact areas
- Mesh density
- Loading and boundary conditions

The simulations also provided data for further investigations such as life cycle prediction and damage locations.

Overall, the goals of the project were achieved. The SHM methods that would be able to validate a military based or rail-maintenance vehicles were investigated. By the help of FEA and experimental data, these methods were verified and a sample proved their agreement. So, these methods can be utilized to perform SHM on the said vehicles in the future.

5.2. Limitations

The limitations on this research were brought by the quality of the samples and the restrictions on the number of elements due to the ANSYS academic version. These factors could have affected the accuracy of the results. Also, there were occurrences where further validation was requested. There were no means to check micro deformations on the sample due to fatigue. The comparison between unfatigued sample and fatigued sample couldn't be analysed due to limitations on the testing equipment provided by the university.

5.3. Conclusions

The impact hammer used for modal testing proved its efficiency. It was a very fast method to obtain natural frequencies of the system. Highly sensitive sensors were chosen. Modal analysis proved to be solely dependent on mass and stiffness of the structure. It was concluded that the sensor attachment affected the natural frequency of the sample.

Comparison of the experimental impact testing results and the simulation data showed great similarity. Each correlation between the mode shapes were observed to be at different rates. As the difference between these two data sets was found to be at maximum 1.12 percent, the requisite resemblance of the experiment was achieved before further analysis. The fatigue analysis results showed good correlation where displacements and strain were similar. The strain damage was present which resulted in cyclic hardening of the sample. As shown by the plot of LVDT sensor location, the sample bent gradually less over time. With the corroboration of the results, the locations for damage and sample cyclic life were predicted.

The development of the models and generation of accurate simulations revealed the effectiveness of ANSYS which could calculate the frequencies for modes of vibration, mode shapes, directional and total deformations. These illustrate the closeness of the simulation to the real structures' behaviour. Therefore, accurate damage and fatigue predictions could be made which can enhance not only the quality and efficiency of SHM but also the costs, processes and time demanding services.

5.4. Further Work

Further work was mentioned in some of the previous sections. The models could be tested without any licence restrictions and accuracy of the results could be checked again especially for the fatigue analysis. Numerical errors in the solution could be endorsed. The fatigue damage could be examined further with more resources. These methods could be applied on a full vehicle for a comprehensive test. Results could be validated against the professional data given by companies.

6. Project management

6.1. Project and Time Management

This report was about the validation of the SHM methods which contributed to the group reports aim. From the beginning, regular meetings and planning were apparent in the project. A group page was created online to enable fast and effective communication, sharing and editing of documents. By this method, decisions like the group meeting times could be made rapidly. In the first stages, the group meetings were focused on defining objectives of the project and members researching the areas that they were most interested in regarding their talents, interests and educational expertise. Then based on everyone's strengths and opinions, the workload was shared and group was divided into 2 subgroups to manage the tasks. The members in the same subgroups formed close working relationships.

Thee communication was clear and weekly meetings were held to track progress. A compliant project schedule was created. The findings of this report were shared with other subgroup members to ensure coherence but collaboration on individual parts were avoided. The necessity to conduct experiments was established early in the first term, so a lab induction was booked for an available slot and materials were purchased. Consultations were undertaken with the project supervisor several times to manage project scope and receive guidance.

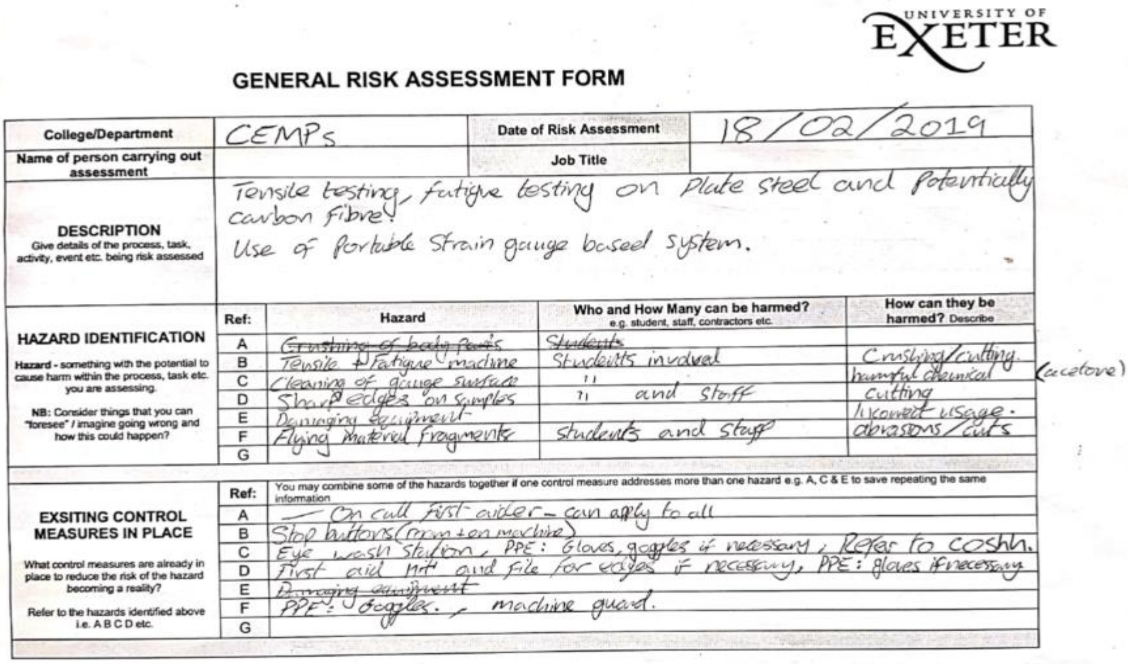
The workload of the individual report was managed periodically throughout the term and it was balanced with leisure activities in order to assure the balance between personal growth and knowledge advancement in the last year of university. Gradual progress was made and experiments were completed. The report writing complied with the project schedule to ensure there was enough time left for critical analysis and editing.

6.2. Budget

The group was divided into implementation and model-based subgroups to achieve the group project aims. As this report aimed to validate the SHM methods by comparing experiments and computational data, it featured in the model-based subgroup where experiments were involved. This meant that most of the budget was spent for purchasing the samples and testing equipment. Purchases were not made individually. A total of £211.49 was spent collectively by the model-based sub group which left £323.41 unused. The experiments involved utilizing university resources designated for CEMPS students.

6.3. Health and Safety

Some risks were involved in the experiments. These included using a soldering iron, being close to machinery and being in the workshop environment. The hazards and possible stakeholders were identified. So, a lab induction session was booked with the university staff to get familiar with the workshop environment which provided the insight to conduct these experiments safely. Risks were mitigated by following procedures and getting guidance form laboratory technicians. A part of the risk assessment form is shown as below.



UNIVERSITY OF EXETER

GENERAL RISK ASSESSMENT FORM

College/Department	CEMPs	Date of Risk Assessment	18/02/2019
Name of person carrying out assessment		Job Title	
DESCRIPTION Give details of the process, task, activity, event etc. being risk assessed	Tensile testing, fatigue testing on Plate steel and Potentially carbon fibre! Use of Portable Strain gauge based system.		

HAZARD IDENTIFICATION	Ref:	Hazard	Who and How Many can be harmed? e.g. student, staff, contractors etc.	How can they be harmed? Describe
Hazard - something with the potential to cause harm within the process, task etc. you are assessing.	A	~~Crushing of body parts~~	~~Students~~	
NB: Consider things that you can "foresee" / imagine going wrong and how this could happen?	B	Tensile & Fatigue machine	Students involved	Crushing/cutting.
	C	Cleaning of gauge surface	"	harmful chemical (acetone)
	D	Sharp edges on samples	" and Staff	cutting
	E	Damaging equipment		Incorrect usage.
	F	Flying material fragments	students and staff	abrasions/cuts
	G			

EXSITING CONTROL MEASURES IN PLACE	Ref:	You may combine some of the hazards together if one control measure addresses more than one hazard e.g. A, C & E to save repeating the same information
What control measures are already in place to reduce the risk of the hazard becoming a reality?	A	— On call first aider – can apply to all
Refer to the hazards identified above i.e. A B C D etc.	B	Stop buttons (room + on machine)
	C	Eye wash Station, PPE: Gloves, goggles if necessary, Refer to COSHH.
	D	First aid kit and file for edges if necessary, PPE: gloves if necessary
	E	~~Damaging equipment~~
	F	PPE: Goggles., machine guard.
	G	

Figure 18 – Completed Risk Assessment Form

7. Contribution to group functioning

This report contributes to the model-based subgroup that was mentioned earlier in this chapter. The aim of this report was to validate the SHM methods that were applied on a sample chosen from the target vehicle. Fatigue and modal analyses were applied on a sample which was also tested by another group member who was developing a portable SHM system. So, this validation made the SHM system results reliable which was also required by the industry standards. The potential of FEA validation was also implemented. The findings were passed onto a different member of the group.

Regular group meetings were attended and decisions were made aligning with the group projects aim. Communication was maintained professionally, Also, the experiments were conducted with another group member so clear communication and positive work environment was ensured.

8. References

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