FATIGUE LIFE PREDICTION FOR SMALL COMPONENT WELDS

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DECLARATION

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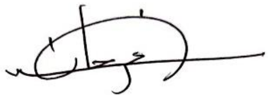

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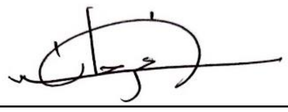

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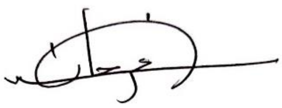

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LIST OF ABBREVIATIONS

3D	3-Dimensional
CAD	Computer Aided Drawing
CPU	Central Processing Unit
FEA	Finite Element Analysis
FEM	Finite Element Method
FFT	Fast Fourier Transform
HAZ	Heat Affected Zone
PMZ	Partially Melted Zone
THAZ	True Heat Affected Zone
USM	Universiti Sains Malaysia

ABSTRAK

Hampir semua struktur mekanikal yang menggunakan kimpalan sebagai kaedah penyambungan akan terdedah kepada kegagalan lesu apabila beban semasa operasi dikenakan secara berulang. Pada mesin kuih loyang separa-automatik, sambungan kimpalan yang menguhubungkan acuan bunga ke rangka menjadi bahagian yang paling kritikal dalam struktur tersebut memandangkan acuan tersebut mudah tertanggal dari rangkanya selepas masa operasi yang lama menyebabkan kekurangan dalam kuantiti pembuatan kuih loyang. Antara factor yang disyaki menyebabkan masalah ini adalah lesu getaran dan lesu haba. Lesu getaran berpunca dari proses goncangan rangka acuan manakala lesu haba berpunca dari perubahan haba semasa proses mencelup dan menggoreng yang berulang. Dengan mengaplikasikan kaedah unsur terhingga (FEA) menggunakan perisian *ANSYS Mechanical*, simulasi untuk kedua-dua senario telah dijalankan untuk mengkaji kesan lesu sambungan kimpalan pada rangka acuan. Di akhir kajian ini, keputusan menunjukkan bahawa lesu haba menjadi penyebab utama kepada kegagalan yang berlaku kepada sambungan kimpalan tersebut. Tegasan maksimum yang berlaku pada rangka acuan disebabkan getaran ialah 12.6 MPa. Jumlah tegasan itu terlalu rendah untuk menyebabkan kerosakan lesu memandangkan ianya berada di bawah had ketahanan lesu untuk bahan yang digunapakai. Keputusan untuk analisis lesu haba menunujukkan yang rangka acuan dengan 4 sambungan kimpalan ialah model yang paling kritikal dalam keseluruhan struktur rangka acuan. Jangka hayat lesu untuk model ini ialah 21 kitaran proses celupan dan gorengan. Tambahan pula, kaedah grafik untuk meramal jangka hayat lesu pada mana-mana nilai tegasan dapat dilaksanakan dengan memplot keputusan tegasan-jangkahayat untuk semua model rangka acuan. Satu kajian bereksperimen akan diperlukan untuk menyokong keputusan yang diperolehi dari simulasi memandangkan beberapa parameter yang berlaku secara alami semasa kaedah bereksperimen tidak dapat disertakan dalam simulasi.

ABSTRACT

Almost all mechanical structures that adopts weld joints as connection method is susceptible to fatigue failure when operating load is applied repeatedly. In semi-automatic honeycomb cookies dipping machine, the weld components connecting rose-shaped mould to the moulding frame becomes the most critical location in the structure since the mould tend to be detached from the frame after long operational time resulting in reduction of manufacturing quantity. The suspected causes of this problem are due to vibration fatigue and thermal fatigue. Vibration fatigue is resulting from repetitive shaking process whereas thermal fatigue resulting from repetitive thermal changes during dipping and frying process. By applying finite element method (FEM) using ANSYS Mechanical software, simulations for both scenarios have been conducted to study the fatigue behavior of weld components on moulding frame structure. At the end of this study, the results show that the thermal fatigue is the main factor to the failure that occurs on the weld components. The maximum stress that occurs on the moulding frame structure due to vibration is 12.6 MPa. The stress magnitude is too low to induce fatigue damage since it far below the fatigue endurance limit of materials applied. The results for thermal fatigue analysis show that the moulding frame with 4 weld joints is the most critical in the whole moulding frame structure. The minimum fatigue life for this model is 21 cycles of dipping and frying process. Furthermore, the graphical approach of fatigue life prediction at any stress value has been achieved by plotting the stress-life (S-N) results for all moulding frame models. An experimental study will be required to support the reliability of the results obtained from the simulation since a few parameters that naturally occur on experimental approach such as welding flaws cannot be included in simulation.

CHAPTER 1

INTRODUCTION

1.1 Overview and Project Background

Fatigue in material is a failure mechanism that occurs in structural elements as a result of a high number of repetitive and cyclic stresses over a lengthy period of time. Fatigue failures in mechanical structures, which usually initiated in the form of microscopic crack, are nearly always caused by alternating stresses that are much below the material's yield strength. The number of cyclic stresses that a structure can sustain before fatigue failure occurs is known as fatigue life whereas fatigue strength is known as the highest stress that a structure can withstand for a given number of stress cycles before fatigue failure occurs. Both parameters are commonly used to describe the fatigue behavior of a structure or material. Fatigue cracks are commonly caused by abrupt changes in geometry or notch locations, both of which are prone to high stress concentration [1]. The weld joint is one of the most common locations in steel structures where high stress concentration occurs, making it the most likely location for fatigue failure to occur.

Almost any mechanical construction that adopts weld joints as a connection method is susceptible to fatigue failure. Fatigue failure in large structures such as railways, bridges, and aerospace structures can result in life-threatening damages, whereas fatigue failure in small structures such as machinery components can result in malfunction and ineffective operation of the machine. This event occurred in the semi-automatic dipping machine of honeycomb cookies that dealt with the fatigue failure of welded joints due to repetitive vibration and thermal load.

Traditional honeycomb cookies, also known as kuih loyang in Malaysia, are a popular choice for most local festivals. Kuih ros, kuih bunga durian, kuih cap, and kuih goyang are some of the other names for kuih loyang. Traditional method of producing honeycomb cookies is conducted manually by hand using a rose-shaped mould connected to a rod. The mould will be dipped into flour mixture then it will be shaken gently to remove the excessive flour mixture. Then, the mould will be dipped into frying oil for frying process. Sometimes the mould need to be shaken during frying process to remove the honeycomb cookies attached to the mould. The honeycomb cookies can be produced in large quantity by attaching multiple rose-shaped mould into a frame. This method have been developed for rural industry of honeycomb cookies production. However, the movement of the frame is fully controlled by the hand of worker. A semi-automatic machine for the biscuit dipping process is intended as a solution for the delayed production.

Figure 1.1: Honeycomb cookies (kuih loyang)

Figure 1.2: Moulding frame used in rural honeycomb cookies industry

A semi-automatic dipping machine have been developed in the previous project using pneumatic cylinders as actuating device and Arduino as microcontroller. These pneumatic actuators are connected to moulding frame which consist of multiple rose-shaped mould. Weld joints are used to connect the rose-shaped mould to the main frame of the machine. The rose-shaped mould tends to detach after a long period of operation due to repetitive vibration in the shaking process and thermal changes in frying process, resulting in reduction of manufacturing quantity. The repeated vibration and heat fluctuations involved in the shaking and hot oil dipping procedure are suspected to be the main cause to the failure. This occurs as a result of the welded joints' fatigue behavior in response to vibration and heat changes, which is referred to as vibration fatigue and thermal fatigue, respectively.

Figure 1.3: Studied structure of moulding frame

Generally, vibration fatigue is a particular form of mechanical fatigue brought on by the vibration of a structure while it is in use. Vibrations, like other types of fatigue, can start a crack that could spread and ultimately cause the equipment to collapse [2]. On the other hand, thermal fatigue is a particular kind of fatigue failure mechanism that is brought on by cyclic loads brought on by frequent changes in the equipment's temperature. The magnitude and frequency of temperature variations have an impact on the extent of damage. One or more cracks at the component's surface are the most common signs of damage [3]. The fatigue process is typically viewed as controlled by a specific such variable. A load cycle is defined as the duration from one peak in the studied variable to the next peak. In a general case, all cycles do not have the same amplitude. For a superficial discussion, it can, however, be assumed that the fatigue-controlling state variable has the same value at the start and end of each load cycle. In elastic materials, a cyclic load causes a periodic-cyclic stress response. For such cases, the load cycle is easily defined. This is illustrated by the Figure 1.4 below, where stress is the fatigue-controlling state variable. Where σ_m is the mean stress value between peak and valley values, σ_a is the amplitude of the stress value that is applied constantly in each stress cycle with positive and/or negative values, σ_{max} and σ_{min} are the maximum and minimum stress value that being applied in cyclic form during the fatigue loading respectively [4][5] .

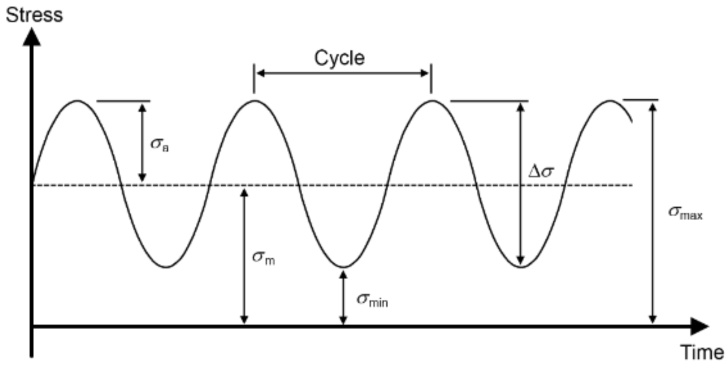

Figure 1.4: Constant stress amplitude over time

1.2 Problem Statement

In steel mechanical structure, weld joint is the most common locations that are exposed to fatigue failure after bearing with high number of repetitive cyclic stresses. This phenomenon which almost always occur in all range of structure's size, whether it is small or large structure. In semi-automatic dipping machine of honeycomb cookies, the rose-shaped mould are primarily connected to its frame by weld joints which have become the most critical part of the structure since the mould tend to be detached from the frame over time due to vibration fatigue and thermal fatigue failure. According to its operational procedure, vibration fatigue is resulting from forced vibration of vertical shaking process whereas thermal fatigue is resulting from thermal stresses due to repetitive hot oil dipping process. Therefore, this fatigue behaviors occurred on the weld joints needs to be assessed to predict the functional lifespan of the moulding frame

1.3 Project Objective

The objective of this project is to analyze the stresses of welded joints in moulding frame that being used to produce honeycomb cookies. The fatigue life of the welded joints in traditional honeycomb cookies moulding frame against vibration and thermal fatigue will be predicted through finite element analysis (FEA) using ANSYS Mechanical software.

1.4 Scope of Research

This project is mainly scoping on the simulation for both vibration and thermal fatigue analysis of weld connection on moulding frame structure. However, important parameters such as the actual motion of the moulding frame and operating temperature of frying oil during production process of honeycomb cookies must be identified because the loads and boundary conditions applied in the simulations depend on these parameters. Therefore, an experimental measurement has been conducted to assess the vibration motion of the moulding frame during shaking process on semi-automatic dipping machine. The acceleration data from the vibration is required for the simulation of vibration fatigue analysis. For thermal fatigue analysis, the operating temperature as well as the steps during dipping process are identified through observation and study of the whole process of honeycomb cookies production. Some of this information are obtained from the manufacturer of honeycomb cookies that use similar design of moulding frame.

The simulation for vibration and thermal fatigue analysis was conducted using ANSYS Mechanical software. Prior to the simulation, the actual dimensions of honeycomb cookies moulding frame were determined through measurement using proper tools. SOLIDWORK software was also used for 3D solid modelling of the moulding frame based on the actual dimension. In ANSYS Mechanical software, different analysis system will be used for each fatigue analysis. Vibration fatigue analysis will applying transient structural analysis which used acceleration data of vibration obtained from experiment for load and boundary condition assignment. Modal analysis was conducted on the moulding frame model as a prerequisite analysis system to the transient structural analysis. For thermal fatigue analysis, thermal transient analysis will be applied. Operating temperature of the frying oil which vary over time will be considered as load and boundary conditions for this analysis.

The main solution intended for both analysis systems is the equivalent stress resulting from the load applied. Fatigue tool in ANSYS Mechanical software was used for both analyses to assess the stress data for fatigue life prediction. Important parameters such as type of fatigue analysis, loading type, and mean stress correction theory are determined. The targeted solution for fatigue analysis is the fatigue life results. The results are represented in contour plot of the studied structure where it shows the available life for the given fatigue analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Fatigue Failure

Mechanical fatigue of materials refers to failure mechanism that occurs in structural elements as a result of a high number of repetitive and cyclic stresses over a lengthy period of time. The resulting damages which are progressive and permanent, start with the propagation of microscopic cracks or fracture if the mechanic limit of the material is reached. Fatigue failure of materials does not occur due to high magnitude of load applied, although it starts after critical number of cyclic and repetitive load that is far below the material's yield strength. The number of cyclic stresses that a material or structure can sustain before fatigue failure occurs is known as fatigue life whereas fatigue strength is known as the highest stress that a structure can withstand for a given number of stress cycles before fatigue failure occurs. Both parameters are commonly used to describe the fatigue behaviour of a structure or material [1].

2.1.1 Phases of Fatigue Failure

The fatigue failure mechanism occurs in microscopic level of the material which involves cyclic deformations of the material. Starting from the initial load application until complete fatigue fail of the material, there are three different phases involve. The first phase is the nucleation phase of the fatigue crack where no crack of any length present in the material and the location of the crack initiation is unpredictable. Cyclic loadings occur simultaneously with the cyclic deformations of the material. Along this process, the materials recovers partially or totally causing its properties to deviate over time and a crack can initiate in critical areas that have high presence of pre-existing defects. Second phase of fatigue failure occurs when the crack is visible and start to propagate along the load bearing plane and as the crack grows, the load supporting area is reduced. In the last phase, the reducing load bearing area is no longer capable to hold the loads applied causing the material to fail instantaneously. This happens because the loads are applied in a small cross-sectional area of the material. Regardless of brittle or ductile material, the fatigue failure always shows a brittle fracture [6].

The three phases of fatigue failure can be represented as in Figure 2.1 below. The variable of horizontal axis represents stress intensity factor whereas the variable in vertical axis represents the speed of the crack propagation based on the number of fatigue failure cycles applied. The fatigue propagation can only be studied in the second phase since the propagation is more linear compared to first and third phases that have unstable and unpredictable propagation [6].

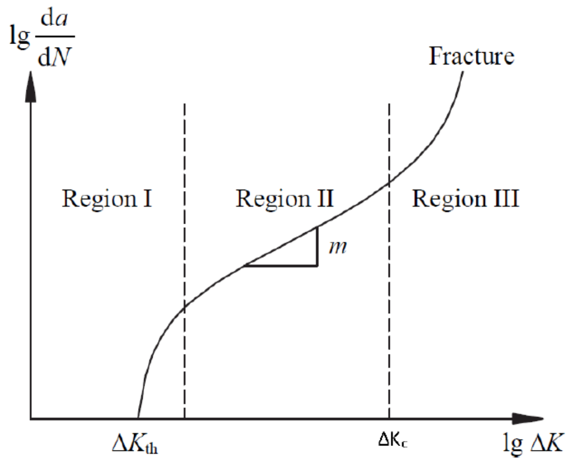

Figure 2.1: Fatigue crack grow rate

2.1.2 Fatigue Stress Cycles

Stress that been applied repeatedly on material or structure can be categorized into two different types which are stress cycles with a constant amplitude, and stress cycles with variable amplitude over time. Distinctive loads but with constant amplitude have been conducted to assess this method, therefore only the first type of stress will be explained here. The stress amplitude, range, frequency and medium value over time can be illustrate in a generic graphic as shown in Figure 2.2 [5].

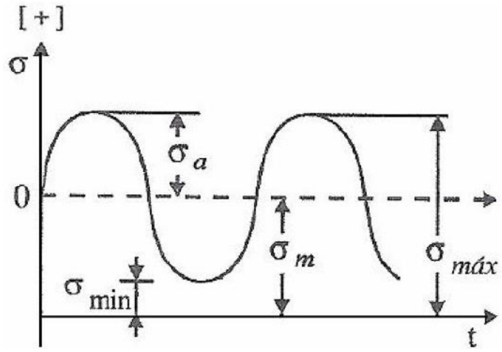

Figure 2.2: Constant fatigue stress amplitude

$$\sigma_m = \frac{\sigma_{min} + \sigma_{max}}{2} \quad (1)$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2)$$

Where σ_m as given in Equation 1 is the mean stress value between peak and valley values, σ_a as given in Equation 2 is the amplitude of the stress value that is applied constantly in each stress cycle with positive and/or negative values, σ_{max} and σ_{min} are the maximum and minimum stress value that being applied in cyclic form during the fatigue loading respectively.

Equation 3 below gives the range between the highest and lowest value of stress applied.

$$\Delta\sigma = \sigma_{max} - \sigma_{min} = 2\sigma_a \quad (3)$$

The stress ratio, R can be expressed as given in Equation 4 below.

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (4)$$

It is possible to have distinct values of R, which specifies the type of fatigue loading, if the σ_m and σ_a have similar values.

- R = 0 means that the loading is pulsing, so it varies from 0 to a tensile load with positive values;

- R = -1 means that the loading is in pure alternating cycle where it changes from tensile to compressive;
- R > 0 means that the load is in fluctuating cycle, so both stresses σ_{max} and σ_{min} are tensile load with positive value.

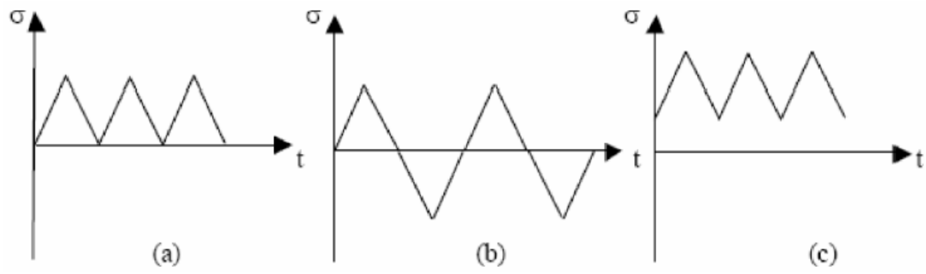

Figure 2.3: Fatigue cyclic with (a) pulsing, (b) alternating, (c) fluctuating load

2.1.3 Mean Stress Effect

Fatigue life is mostly dependant on the amplitude of the stress that occur in the component, but if the component has a mean stress, altering the global stress cannot be avoided. Before operating stresses are introduced, components often carry various types of loads like gravitational or pre-tension, or the input loading may have a mean value. The allowed amplitude of fatigue stress decreases for a given life if the mean stress is more compressive and increases for a given life if the means stress is more tensile. The primary presumption is that means tress linearly influences the permissible applied stress [7].

If the fatigue strength at any mean stress is known, the line indicating the fatigue life may be calculated. The most popular and often used technique for determining modified alternating stress from mean stress is Goodman's Rule. Other mean stress approaches exist as well, such as Gerber and Soderberg’s rules. The Soderberg theory is typically seen as being overly conservative, while most of experimental data generally lie between the Goodman and Gerber theories. For brittle materials, the Goodman theory might be a viable option, while ductile materials are often a good fit for the Gerber theory [8]. In addition, there is one more mean stress theory called Modified Goodman’s theory. Figure 2.4 shows the graphical representations of all mean stress correction theories.

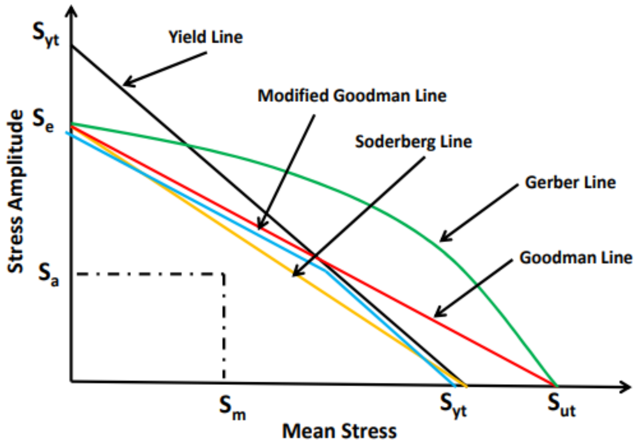

Figure 2.4: Mean stress modification methods

2.1.4 Stress-Life (S-N) Curve

There are three different type of fatigue life methods that can be applied to perform fatigue design or analysis which are Stress-life method, Strain-Life method and Linear-Elastic Fracture Mechanics method. The method that primarily followed in this study is Stress-Life method which associated with Stress-Life (S-N) curve or also known as Wohler curve. According to Stress-Life method, the fatigue life and fatigue strength of material can be determined through experimental tests by subjecting the material to repeated or varying loads of specified magnitude while the load cycles are counted until failure occurs.

The information obtained can be organized in a diagram called the S-N curve or the Wohler curve. In order to establish the curve on the diagram, a fatigue test must be conducted at each stress value so that the allowed corresponding value of fatigue life cycles can be obtained. It is preferable to repeat the fatigue tests for several times since the statistical nature of mechanical fatigue is negligible. The values on vertical axis of an S-N curve are the strength values which represent the properties of the material. The values of strength can be compared with the stress values applied in studied or designed structure to assess the fatigue behaviour [1].

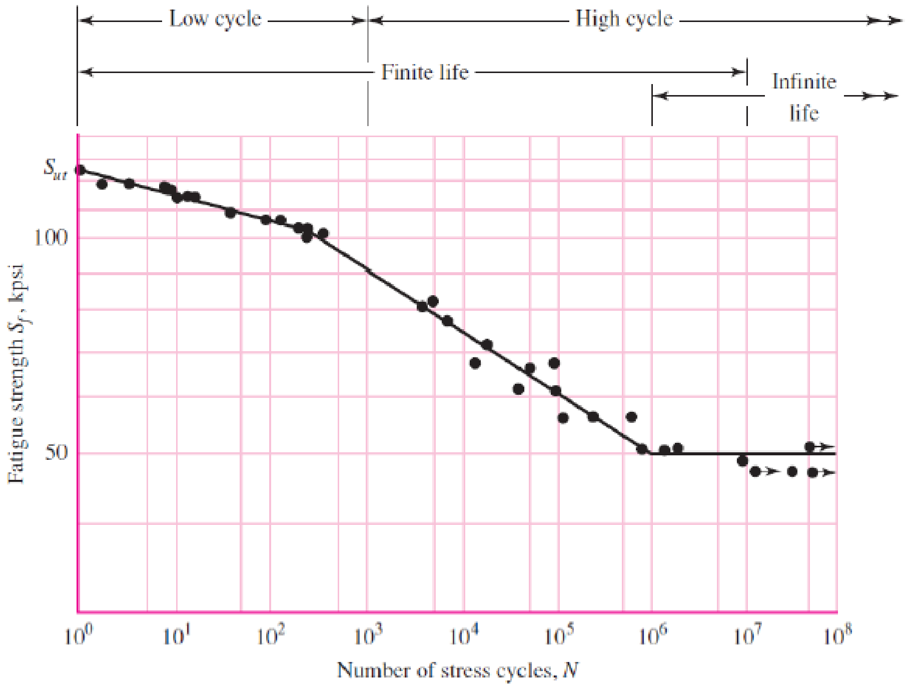

Figure 2.5: S-N curve

There are significant consequences for fatigue life since the S-N curve's connection between stress level and the number of cycles till failure is not linear. The difference between employing an S-N curve's axis in linear (linear-linear) or logarithmic (log-log) scale is seen in Figure 2.6.

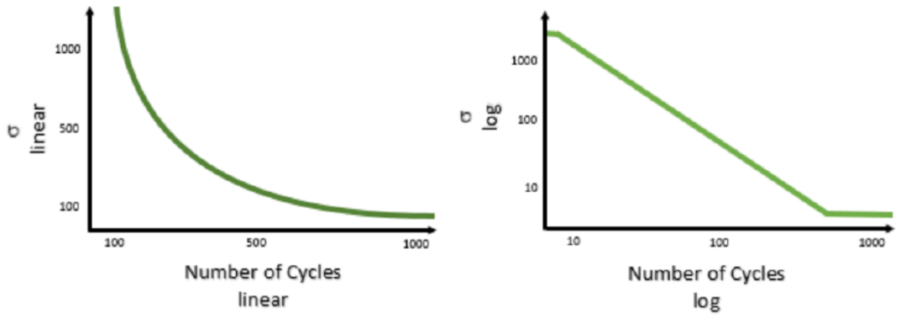

Figure 2.6: curve with linear (a) and logarithmic (b) scale

2.1.5 Fatigue Endurance Limit

In the end of high-cycle fatigue section of S-N curve as shown in figure, the slope curve turns horizontal which represents the infinite fatigue life of the material. It occurs at a stress value called fatigue endurance (S_e) limit that regardless of how large the stress cycles being applied, the material will never fail. Alternatively, a structure or component that being designed for finite fatigue life must be applied with resulting stress amplitude that is lower than the endurance limit of the material [6]. The endurance limit depends on many factors like material properties, presence of pre-existing flaws and surface quality but for most materials it is usually in range of 10^6 to 10^7 load cycles.

The endurance limit does not occur in all materials. For example, non-ferrous metals such as aluminium is considered to have finite fatigue life since there is no such thing as endurance limit making itself exposed to fatigue failure against almost all range of stress amplitude [9]. Figure 2.7 shows the comparison between the S-N curve of a steel and the S-N curve of an aluminium indicated by letter A and B respectively.

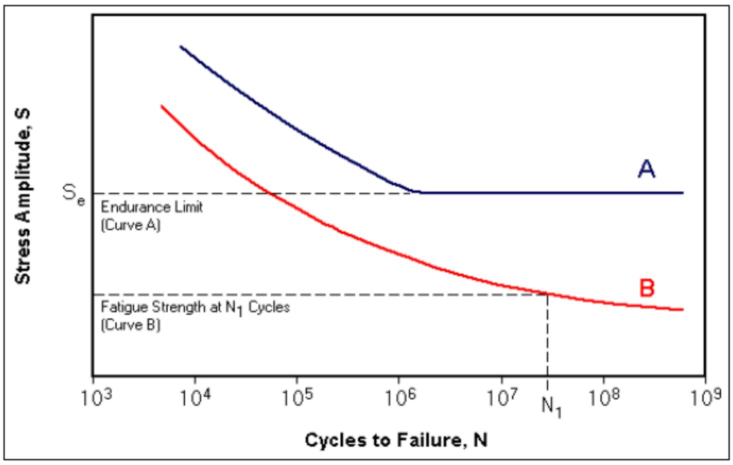

Figure 2.7: Comparison of S-N curves between steel and aluminium [9]

2.2 Welding

Welding is one of the most commonly used permanent joining techniques in wide range of manufacturing industries including automotive, aerospace, civil construction and naval construction. Conventional welding process is conducted by joining two pieces of metal together using filler material which commonly associated with weld metal or weld rod that being applied with concentrated heat source until melting temperature is achieved causing the base metal and weld material to fuse together by metallurgical bond between them. Some other weld methods are not depending on the additional metal like friction welding where two pieces of metal are plastically displace and fused together by heat generated by mechanical friction between them. Welding technique that is one of the oldest and reliable joining technique can be distinguished from other types of mechanical connections such as riveting or bolting.

2.2.1 Welding Effects on Material

During welding, the heating and cooling processes will alter the material structure. The solidification of the material under cooling process will change the microstructure of the material in the form of grain growth. The large grain size formed after the cooling process is undesirable and can be prevented by rapid cooling process of the welded component, since the crack size is dependent on the maximum temperature, time spent at the maximum temperature, chemical composition of base metal and cooling rate [10] [11]. The microstructure in welded joint can be distinguished into different regions. The regions available which represented in Figure 2.8 are fusion zone, Heat Affected Zone (HAZ) and base material which are unaffected from the fusion process of the metals.

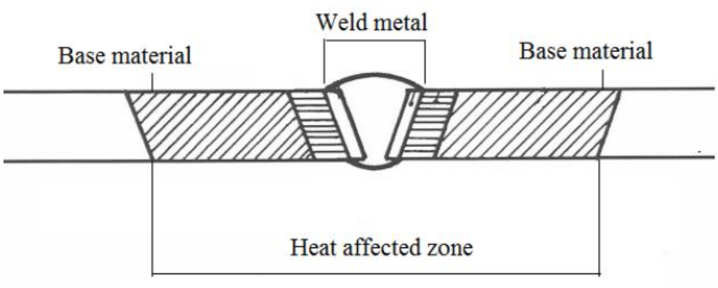

Figure 2.8: Three distinct regions of post-weld metal

The fusion zone is the region where complete melting and re-solidification occur after welding process. The Heat Affected Zone endure different metallurgical reactions due to recrystallization and grain growth. The HAZ can be categorized into two subdivisions which are True Heat Affected Zone (T-HAZ) and Partially Melted Zone (PMZ) [10].

2.2.2 Fatigue in Welded Component

As previously mentioned in this study, the fatigue strength of a material or structure is mainly dependent on the stress amplitude and stress cycles. However, fatigue strength of welded joint could be influenced by many different factors such as material properties, residual stress, weld quality and imperfections. The combination of cyclic stresses from external loading and local stress concentrations, which are residual stresses that localised at the weld toe and root, can limit the fatigue life of a welded joint [12]. The heat-affected zone and weld metal, which result from the unavoidable heat effect during the welding process, become the welded structure's weakest links [13]. Fatigue strength of welded joints can also be affected by plate thickness of elements that are being connected. The fatigue strength of welded joints decreases as plate thickness increases. This arises as a result of higher residual stresses caused by the welding process as plate thickness increases [12].

Afterward, in term of weld and base material, the fatigue strength of welded connections is almost independent of the material strength, which is a unique feature [14]. The rate of crack propagation is wholly unrelated to material tensile strength, and fatigue strength does not improve with increased material strength. This phenomenon occurs in contrast to unwelded material [15]. However, due to differences in crystal structure, strength, and fatigue resistance, the fatigue life of different steels varies. The notch sensitivity of high-strength steels is higher than that of mild steels. Weld geometry must be taken into account when fatigue failure is concerned. Stress concentration in the weld joint could be caused by transitions, notches, or variations in cross section. Roughness produces tiny stress concentrations and lowers fatigue strength, therefore surface quality is also critical. Environmental factors such as corrosion, erosion, and gas-phase embrittlement can all impair the weld joint's fatigue strength. Welded structures subjected to intense temperature activity may have a low fatigue life [16].

2.2.3 Residual Stress in Weld Joint

Residual stress is a stress that remains in the base metal even after the original cause of stress have been removed. Residual stress may contribute to brittle fracture of welded joint especially under multi-axial stress, high loading rate and low temperature conditions. In other word, the strength and fatigue life of welded joints can be highly influenced by the residual stresses remaining in the structure even after it have been cooled. It is essential to include the knowledge of residual stress while assessing the structural integrity of welded structure [17].

When metal structures are joined together by welding technique, a localized fusion zone is generated in the weld joint resulting from high heat input from the arc. Due to the heat conduction, non-uniform temperature distribution occurs followed by non-uniform heat deformation and thermal stresses in the welded joint. As a result after cooling of the welded joint, non-linear plastic deformation and residual stresses are retained within the structure. the intensity of residual stresses as well as its distribution pattern can be determined by several parameters [18].

2.3 Vibration

Vibration is a mechanical phenomenon in which a point or a body experience oscillation. Vibration can be differentiated into to types which are free and forced vibration. Free vibration occurs when an object in rest condition is allowed to move and oscillate without any constraint. On the other hand, forced vibration occurs when a body or a system is applied with external force which lead to a phenomenon called resonance. Resonance may occurs when the natural frequencies of the system are approached by the external force frequencies. The natural frequencies of the system can be excited higher, lower, or annihilated through resonance. The strength and stability of a structure could be compromised if the effect of resonance is not controlled. In fact, vibration becomes the direct cause of damage and failure for most mechanical structure [19].

There are two measurable quantities available for vibration which are amplitude and frequency. The strength of a vibration in terms of displacement is represented by its amplitude whereas The speed of the oscillation from the stationary point is represented by the frequency of a vibration. The number of cycles that a vibrating structure completes in one second is called frequency. In order for easier understanding, vibration can be expressed in many wave forms such as time domain and frequency domain wave forms that are commonly used. A comparison between time domain and frequency domain wave forms is shown in Figure 2.9 below. The vertical axis for both wave forms similarly indicate the amplitude of vibration whereas horizontal axis indicates time and frequency for time domain and frequency domain respectively.

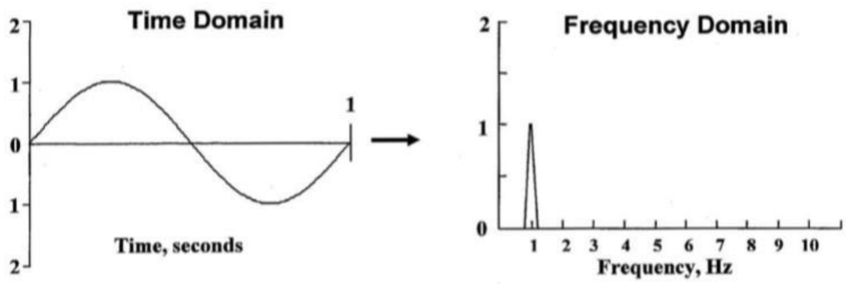

Figure 2.9: Example of a time domain graph and frequency domain graph

2.3.1 Experimental Analysis on Vibration

Experimental analysis is one of the approaches that can be made to study the vibration of a structure. An instrument called accelerometer is utilized to comprehend the vibration's properties which is used to measure the acceleration forces. A program that does the fast fourier transform (FFT) analysis is used to examine the obtained data. The observed component or structure will be attached with an accelerometer, which collects data over time and stores it digitally as acceleration values in the computer. Software will be used to analyse the raw data in order to determine a set of sine wave frequencies and their corresponding amplitudes [20].

2.3.2 Vibration Fatigue

Stress cycles that lead to the fatigue failure are a result of external loads of the structure such as mechanical, thermal, and vibrational load. The type of fatigue failure due to the vibrational load is known as vibrational fatigue. Vibration Fatigue is a specific type of mechanical fatigue that is caused by the vibration of equipment during operation. Like other forms of fatigue, vibrations can initiate a crack which may lead to propagation of the crack and eventual failure of the equipment. For harmonic and random vibration stresses, vibrational fatigue can be studied. The stress load that leads to fatigue failure happens in both circumstances as a result of the structure's own dynamic reaction. Vibrational fatigue is always followed by changes in natural frequency and damping loss factor, both of which can be used to anticipate fatigue failure [21].

2.4 Thermal Analysis

Thermal load is described as temperature that influences the structures, such as the ambient air temperature, solar radiation, indoor air temperature and heat source equipment nearby. The change of temperature in a structure or body causes thermal expansion to the body and subsequently lead to thermal stress which can be described as the main effect of thermal loading. Thermal analysis is the study of temperature change in relation to a material's properties. This approach may be used to study a variety of properties such as mass, size, volume, stiffness heat transmission and temperature distribution. Other concepts can be employed within the method as well. The main goal of the entire discipline is to determine how temperature affects different material's physical properties. Thermal analysis also provide the information on specific heat, coefficient of thermal expansion, thermal stability and composition of the studied structure [22].

Thermal analysis of a material may be done in number of ways, including theoretical formulation, computer modelling and experimental approach. Thanks to the development of powerful computers and software, computational modelling has become a very useful and affordable tool for materials design and research. Computer modelling often can supersede costly experiments and offer more details than that obtained from experimental approach [23].

2.4.1 Thermal Stress

Thermal stress is stress that brought on by a temperature fluctuations in a body. It is crucial to understand their causes and nature since thermal stresses can produce fracture or unfavourable plastic deformation. There are two main causes of thermal stresses which are constrained thermal expansion and temperature gradients established during heating or cooling process. when a solid body is heated or cooled, the internal temperature distribution depending on its size and shape, the material's thermal conductivity, and the rate of temperature change. Thermal stresses can develop as a result of temperature gradients within a body, which are frequently brought on by rapid heating or cooling, where the outside temperature changes more quickly than the inside. Differential dimensional changes act to limit the free expansion or contraction of adjacent volume elements within the object. For instance, during heating, a specimen's outside will have grown more than its inside since it is hotter there [24].

2.4.2 Thermal Expansion

Thermal expansion is known as the tendency of a body to expand in volume in reaction to change in temperature. When a material is heated, the individual particles inside it move more erratically, maintaining a higher average separation in the process. It is extremely rare for materials to shrink as the temperature rises; this phenomenon only happens in a small number of temperature ranges and has a restricted size. The material’s coefficient of thermal expansion typically fluctuates with temperature and is calculated as the amount of expansion divided by the change in temperature [24].

2.4.3 Thermal Fatigue

Discussing about thermal fatigue, it has been discovered that components subjected to alternating heating and cooling will start to crack and eventually fail over time. Thermal fatigue is the name given to this phenomena. Damage typically appears in the form of one or more cracks at the surface of the component. Thermal fatigue cracking is thought to be caused by two factors. Firstly, a change in temperature causes thermal expansion or contraction in the material. Thermal strains occur when surrounding material or external restrictions prevent this expansion. Thermal fatigue is caused by cyclic thermal loads in the same way as mechanical stresses do. Second, materials show time-dependent deformation, such as creep, at high temperatures. Failure is caused by a combination of creep and fatigue. Creep becomes increasingly noticeable as the temperature rises and the exposure time lengthens [25].

Thermal cycles result in fatigue degradation and fracture expansion. Thermal fatigue loading is a term used to describe a load that results from cyclic pure thermal loads, i.e., thermal loads brought on by internal restrictions. The term thermomechanical fatigue is used if the loads develop as a result of external limitations or forces. When the highest temperature also coincides with the highest stress, the loading is said to be in-phase, and when it also coincides with the lowest stress, it is said to be out-of-phase. Typically, cyclic thermal loads result from the rapid heating or cooling of a component surface, such as when fluids of various temperatures are turbulently mixed together. Thermal loads have the feature of being higher at the surface and decreasing inside the component. The strain controls the loading. There is always a surface of zero stress in the component since the stresses are self-equilibrating [25].

2.5 Overview of Finite Element Method

The finite element method (FEM) or finite element analysis (FEA) is a numerical approach that may be applied to solve a wide range of engineering problems. Using FEA, even the most complex stress problems can be solved. An FEA usually consists of three principle steps [26]:

i. Pre-processing: Pre-processing step involves the construction of the studied model. The geometry of the model is divided into several discrete subregions or elements which are joined at discrete nodes.
ii. Analysis: The finite element code itself creates and solves a system of linear or nonlinear algebraic equations using the dataset that have been prepared in pre-processing step. Large element libraries containing elements suitable for a variety of issue kinds may be found in commercial programmes.
iii. Post-processing: In a typical postprocessor presentation, coloured contours reflecting the model's stress levels are superimposed on top of the model to create a full-field image resembling experimental or photo elastic findings.

ANSYS is an FEM package crated by ANSYS Inc. having the capabilities ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis. In the industrial setting, it is frequently used to predict how a physical system would react to structural loads, temperature, fluid, and electromagnetic influences.

Numerical modelling is critical in many domains of technology. Many design and technology problems can be avoided at the design stage thanks to computer simulation and analysis of the results, which saves money. In case of assessing the fatigue behaviour of a structure, the locations that prone to high stress concentration and fatigue failure can be predicted accurately in structure with complex shapes. Camarao et al. (2010) have conducted a study to evaluate the fatigue life of fillet welded joint that connecting a rectangular beam to a square plate using FEA in ANSYS software. This study confirmed that the fillet weld joint experienced the highest equivalent stresses after exerted with certain magnitude of force. The simulation also predicted the fatigue life of the structure using hot spot stress method. The results from simulation are compared with the one from experimental and analytical study using similar model of structure. The finite element model was validated since the percentage error of the results are small after comparing with experimental and analytical study [27].

2.5.1 Computational Challenges in Welding Simulation

Welding analysis is a vital in engineering study, and it's frequently used in fabrication because of the benefits of better structural performance, lower costs, and ease of application. Welding, on the other hand, causes irreversible deformation and residual stress in the material [28]. There are over 20 types of welding flaws including cracks, porosity, worm holes, inclusions, lack of penetration, lack of fusion, lack of fit, undercut, excessive weld overfill, inadequate weld throat, root overfill, misalignment, weld sag, incomplete root, cold lap, arc strike, sputter, and others [29]. With all of these flaws, determining the simulation parameter will be difficult. One of the key issues in welding simulation is material modelling, which is compounded by the unpredictable net heat input [30].

2.5.2 Adaptive Mesh Technique

An adaptive mesh technique have been developed in three-dimensional numerical simulation of the welding process by MARC software. The adaptive mesh method creates a thick mesh that moves simultaneously with the heat source. Any section of the mesh that is further from the heat source is considerably coarser, which saves a lot of CPU time. The adaptive mesh approach can save CPU time by about one-third, according on the calculation time comparison [31]. In traditional FEA, the accuracy of solution increases as the number of element increases as the size of element decrease. Applying the adaptive mesh technique, solutions are conducted by using different element size which in increasing order. Mesh density will be chosen when the result’s difference is insignificant from one elements size to another. As example, the top end of a 2D bracket model is constrained while the bottom right edge is subjected to a shear force. As demonstrated, this causes a peak stress in the fillet. The curve demonstrates that the peak stress in the fillet increases as the mesh density increases. Increasing the mesh density any further results in only slight increases in peak stress. In this scenario, increasing the number of pieces per unit area from 1134 to 4483 only results in a 1.5% increase in stress [32].

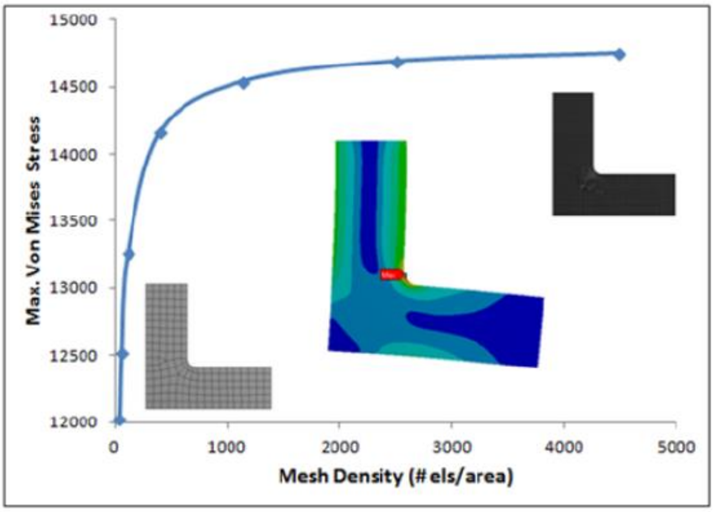

Figure 2.10: Stress sensitivity to mesh density

Figure 2.11 shows the difference results between coarse mesh and finer mesh found from above investigation.

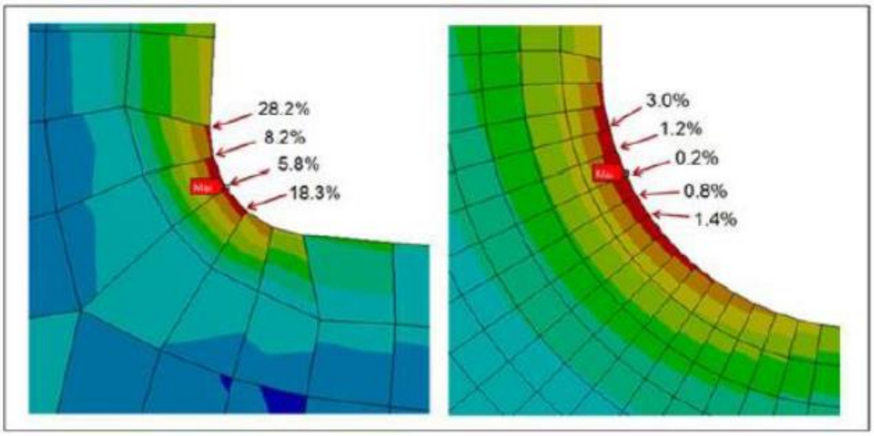

Figure 2.11: Relative difference in stresses at shared nodes for coarse mesh (left) and finer mesh (right)

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will be mainly comprising the methodology for the simulation of vibration fatigue and thermal fatigue of moulding frame using ANSYS software which summarized by the flowchart as shown in Figure 3.1 below. Methodology for experimental measurement on the vibration of moulding frame will also be discussed which involved related procedure and apparatus. For simulation, vital parameters such as project schematic, model geometry, material selection, boundary conditions and analysis systems will be explained thoroughly. The methodology for this project is fully done based on the knowledge gained from the literature study and some research.

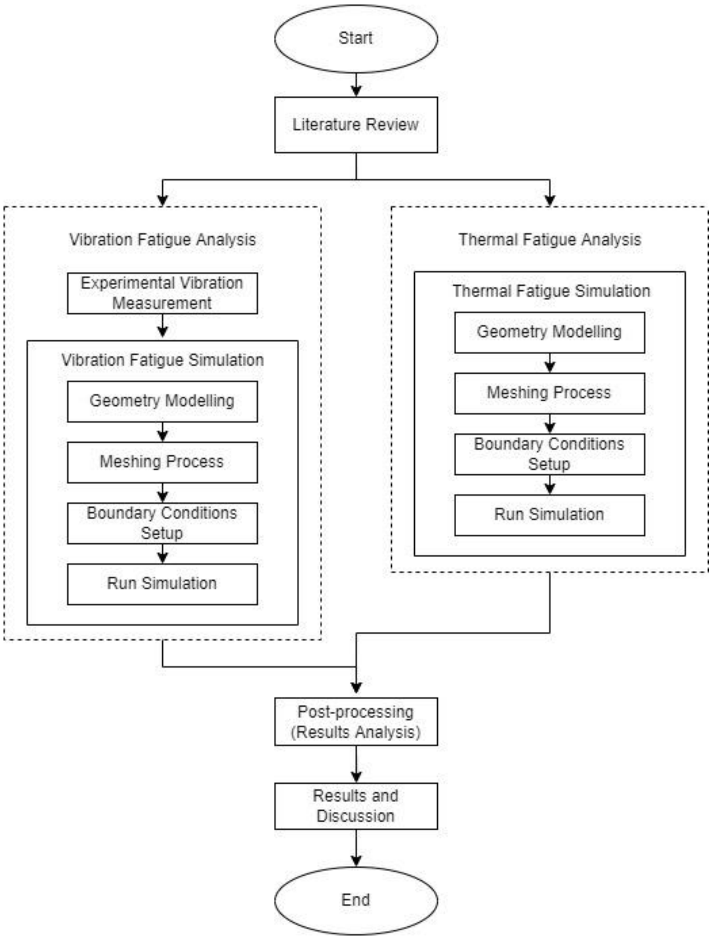

Figure 3.1: Project flowchart

3.2 Experimental Measurement on the Vibration of Moulding Frame

To simulate the vibration of moulding frame structure in ANSYS software, real-time acceleration data of the structure during vibration process need to be obtained. This data can only be evaluated through experimental measurement using appropriate apparatus and equipment.

3.2.1 Apparatus and Equipment

The most influential apparatus for this experiment is the accelerometer and it will be used as a sensor to measure the dynamic acceleration of the moulding frame structure. Its response is very sensitive making it capable of detecting slight excitation that occur on the structure. Dynamic signal analyzer will be used to resolve the magnitude and phase input signals from accelerometer in both time and frequency domain. The dynamic signal analyzer is integrated with a computer to read out and display the data obtained using LMS Xpress software. Figure 3.2 below shows the schematic layout for this experiment.

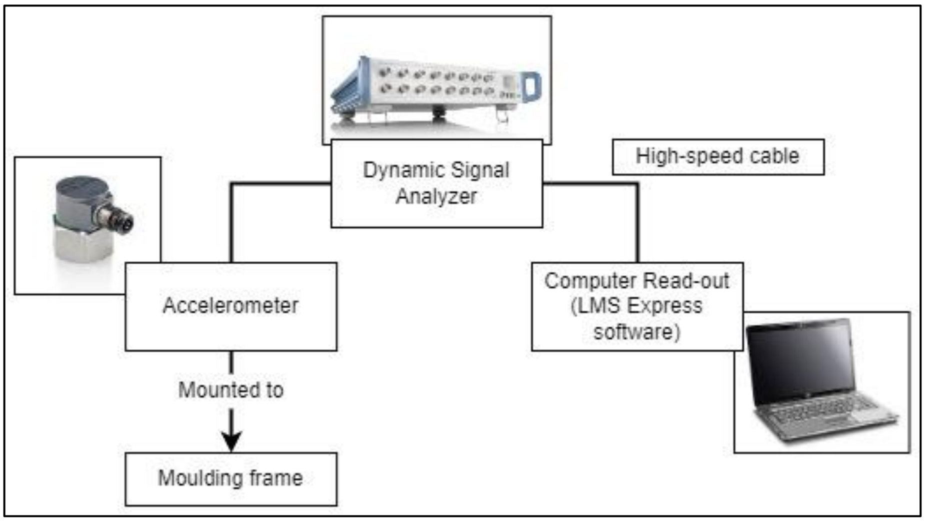

Figure 3.2: Schematic layout for vibration experiment