UNIVERSITI TEKNOLOGI MARA

EFFICIENT MODELLING AND ACCURATE ANALYSIS OF THE DYNAMIC BEHAVIOUR OF A HI-LOK FASTENED STRUCTURE

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CONFIRMATION BY PANEL OF EXAMINERS

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ABSTRACT

The use of Hi-Lok fasteners in aircraft structure assemblies is widespread and crucial, necessitating accurate and computationally efficient modelling technique to analyse their dynamic behaviour. This study proposes and evaluates finite element (FE) modelling techniques specifically tailored to Hi-Lok fasteners, aimed at representing and investigating the dynamic behaviour of a physical Hi-Lok fastened structure in terms of natural frequencies and mode shapes. Four distinct techniques, each employing different FE representations, are created using MSC Software packages to represent the physical structure. The predicted dynamic behaviour obtained from the four FE models are systematically evaluated with experimental modal analysis (EMA) counterparts with respect to natural frequency discrepancies, computing time, and disk storage requirements. The evaluation demonstrates that Technique 4, which uses simplified one-dimensional beam representations of Hi-Lok fasteners, accurately predicts the dynamic behaviour of the physical structure with 98.4% accuracy, while maintaining low computational speed and the lowest disk space consumption among the approaches investigated. This validated modelling strategy proposed in this study therefore offers practical guidance for researchers and engineers seeking to efficiently and accurately predict the dynamic behaviour of aircraft structures incorporating Hi-Lok fasteners.

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LIST OF SYMBOLS

Symbols

x	Vector of Displacement
x	Vector of Velocity
x	Vector of Acceleration

LIST OF ABBREVIATIONS

Abbreviations

CAD	Computer-Aided Design
COMAC	Coordinate Modal Assurance Criterion
EMA	Experimental Modal Analysis
FE	Finite Element
FEM	Finite Element Method
MAC	Modal Assurance Criterion

LIST OF NOMENCLATURE

Nomenclatures

c	Damping Matrix
F	Force Matrix
k	Stiffness Matrix
M	Mass Matrix
t	Time

CHAPTER 1
INTRODUCTION

1.1 Research Background

Mechanical fasteners, especially bolted joints and Hi-Lok fasteners have been widely used for decades in various industries for the assembly of structures [1]. This is due to the essential feature of fasteners that it is easy to assemble and disassemble [2], as well as their simple configuration and low cost [3]. In addition, they play an essential role in the dynamic response of the structure. The added flexibility that fasteners bring has a strong effect on the dynamic response of the structure. This is because much of the energy is lost at the joint during dynamic loading [4], [5]. Despite the fact that fasteners improve damping properties and minimise the size of a structure [6], the dynamic behaviour of assembled structures with fasteners is not well understood.

The dynamic behaviour of a fastened structure can be efficiently predicted using appropriate FE modelling. Several factors, such as the modelling of bolts, joint interfaces, damping and boundary conditions, can contribute to the development of an efficient FE model of bolted joints [6]-[8]. Nonetheless, no study has combined all these main factors to create an efficient FE model of the structure with Hi-Lok fasteners and integrate it into the FE model updating.

Efficient FE modelling can be developed using the FEM, which is also an effective tool for predicting the dynamic behaviour of an assembled structure through normal modes analysis. However, the FEM has its limitations as simplification of the model is always required to minimise the high computational cost. At the same time, it must produce an accurate representation of the assembled structure with fasteners [9], [10]. A simplified FE model leads to different assumptions and needs reference data for validation [11]. Therefore, an EMA is required as a reference to accurately determine the modal parameters of the assembled structure with fasteners.

EMA is a method for extracting the modal parameters of the substructures and the assembled structure with fasteners. The measurements of the input and the resulting responses translated into FRF can be used to determine the natural frequencies, mode shapes and damping ratio [11], [12]. EMA is not only an important means of validating the results of the FE model but also serves as reference data for the FE model updating.

The FE model updating is used to improve the accuracy and reliability of the initial FE model so that the predicted dynamic behaviour matches the experimentally measured modal parameters as closely as possible [13], [14]. Material and physical properties such as Young's Modulus, Poisson's ratio, shear modulus, mass density, thickness and stiffness are the updating parameters commonly used by researchers. The parameters obtained must respond to the modal parameters of the FE model. They can be systematically adjusted within the specified range to be as close as possible to the experimental results [15]. However, the selection of potential candidates for the updating parameters and the determination of the appropriate number of updating parameters and responses to improve a FE model of a fastened structure considering the test model remains challenging and requires a methodologically rigorous approach.

1.2 Motivation for This Work

The design and performing capability of load-bearing structures under high-performance sectors such as aerospace and automotive together with defence relies heavily on mechanical joints. The joints operate to transmit weight between supporting components and modify system flexibility along with resonance features and lifespan expectancy. The Hi-Lok fastener stands out today as a common solution in aerospace applications because it presents lightweight design benefits combined with easy installation along with reliable preload outcomes. The insufficient understanding of joints that use Hi-Lok fasteners exists despite their status as a widespread solution.

This investigation examines aerospace structures under escalating stress conditions because joints suffer complex dynamic responses from aerodynamic changes as well as engine vibrations together with temperature variations. The high-frequency and high-amplitude dynamic loads exhibit gaps in understanding regarding the long-term behaviour of joints assembled with Hi-Lok fasteners because of their torque-limiting break-off collar design which enables enhanced preload consistency. The dynamic response of these joints demands complete understanding because it directly affects the structural system integrity and reliability in all safety-critical applications particularly wing-body attachments and fuselage sections.

During dynamic loading the system manifests several complications including fretting wear combined with preload relaxation and joint stiffness degradation and resonance-induced failures which remain hard to identify through standard inspections.

The energy dissipation process takes place primarily at joints which also modifies the way the entire structure responds to its global modal behaviour. The assessment of Hi-Lok fastened structures requires detailed studies regarding their vibrational and modal characteristics. Scientists must understand how different joint parameters influence both the short-term system dynamics and long-term product durability through investigative analyses of clamping force and material interface and installation accuracy.

EMA now receives recent advancements alongside FE modelling of joint interfaces that offer new possibilities to conduct in-depth studies about these effects. The research uses validated simulations in conjunction with experimental testing to produce an extensive understanding of Hi-Lok jointed structures during dynamic performance. The study will provide better predictability of the joint damping mechanisms and joint stiffness changes alongside failure risks when structures undergo operational loading.

This research needs to fill existing knowledge deficits about the dynamic behaviour of mechanical joints fastened by Hi-Lok fasteners. Investigating the vibro-acoustic behaviour and structural mode coupling enables the research to develop valuable knowledge that can help design advanced mechanical assemblies for high-performance systems.

Moreover, the results of the current study are likely to assist the further advancements of structural health monitoring and predictive modelling in aerospace engineering where the number of available computational resources is usually limited. The simulations used to establish simplified joint representations therefore contribute to the optimized work on dynamic testing and the calibration of the model.

1.3 Problem Statement

The presence of Hi-Lok fasteners in an aircraft assembled structure has a significant effect on changing the dynamic behaviour of the structure, and investigation of the behaviour is crucial to avoid failure of the structure due to resonance [16], [17]. However, the dynamic behaviour of Hi-Lok fastened structure is highly dependent on the stiffness of the fastener interfaces and the fasteners.

Hi-Lok fasteners have wide scope of usage in assembled structures of the aircraft and the role that they play in the dynamic behaviour of the structure is critical. Inaccurate prediction of the dynamic characteristics of such fastened structures may give rise to resonance-related failures with serious risks about structural integrity and flight safety [16], [17]. The dynamic response of Hi-Lok fastened assemblies is strongly governed by the stiffness for the fasteners, the joint interfaces, which need to be modelled accordingly to get reliable results.

Despite their importance, currently there is a lack of an accurate and computationally efficient modelling technique for representing Hi-Lok fasteners in the dynamic analysis. Existing approaches are mostly based on detailed FE models based on three-dimensional solid elements. Although these models are able to represent local fastener behaviour, they are impractical for representing large or complex structures because of the large number of degrees of freedom, high computational cost and large data storage requirements [18], [19]. As a result, such approaches are not appropriate for repeated analyses, models update and early-stage design applications.

Furthermore, the joint interface stiffness properties of joint interfaces and Hi-Lok fasteners are not easy to quantify and are usually over simplified or ignored in the traditional simplified models, yielding incorrect predictions of natural frequencies and mode shapes. This limitation exposes an important relationship between the accuracy of the modelling and the feasibility of the computation that is a crucial limitation in existing fastener modelling practices.

Therefore, a clear need exists for a simplified, yet reliable modelling approach able to accurately model the stiffness effects of Hi-Lok fasteners, as well as joint interfaces, that can significantly involve simplification and reduction of computational complexity. Addressing this problem would make it possible to perform more efficient dynamic analysis, experimental model validation and update, and increase confidence for the prediction of resonance behaviour of the aircraft assembled structures.

1.4 Research Objectives

The goal of this study is to propose an accurate and efficient modelling technique for Hi-Lok fasteners that can be reliably used to investigate the dynamic behaviour of the assembled structure with Hi-Lok fasteners. To achieve this goal, the following three specific research objectives are defined:

a) To develop a 1D element-based FE modelling technique for accurately representing the natural frequencies and mode shapes of the physical Hi-Lok fastened structure.

b) To determine the natural frequencies and mode shapes of the Hi-Lok fastened structure using the proposed modelling technique, and EMA.

c) To evaluate the efficiency and accuracy of the proposed modelling technique by comparing the predicted natural frequencies and mode shapes with their EMA counterparts.

1.5 Research Question

In an attempt to propose an efficient, economical and reliable modelling capable of representing the dynamic behaviour of an assembled structure with Hi-Lok fasteners and to achieve the objectives of this research, the investigation revolves around the following research questions:

a) How can 1D elements be formulated to accurately represent the stiffness and mass of Hi-Lok fasteners for predicting the natural frequencies and mode shapes of the Hi-Lok fastened structure?

b) How accurately can the proposed modelling technique predict the natural frequencies and mode shapes?

c) How well does the proposed modelling technique predict the natural frequencies and mode shapes in terms of accuracy and computational efficiency when compared with their EMA counterparts?

1.6 Significance of Study

This study proposes an accurate and efficient analytical model capable of representing the dynamic behaviour of Hi-Lok fastened structures. The development of an accurate and efficient modelling and prediction for the dynamic behaviour of Hi-Lok fastened structures remain a major research challenge. There is a need to carry out this research because the research results will:

a) Contribute to the current body of knowledge in structural dynamics, especially to FE modelling and updating the dynamic behaviour of an assembled structure with Hi-Lok fasteners.

b) Contribute to solving industry-wide problems, e.g., in the aerospace, automotive, machinery, energy, construction and marine industries, which face numerous challenges in the design, manufacture, operation and maintenance of structures with Hi-Lok fasteners.

1.7 Thesis Scope and Limitation

This study is limited by the following:

a) The study uses an assembled structure with Hi-Lok fasteners. The assembled structure consists of two components, made of aluminium, joined with four Hi-Lok fasteners.

b) The investigation shall include the determination of the modal parameters (natural frequencies and mode shapes) of the substructures and the assembled structure with Hi-Lok fasteners using FE normal modes analysis and EMA.

c) FE normal modes analysis is performed with the NASTRAN programme of the available commercial packages, while the EMA is performed with an impact hammer using the roving accelerometer method.

d) Both FE normal modes analysis and EMA are performed with free-free boundary conditions. No constraint is assigned for the normal modes analysis, while for the EMA, the test specimens are suspended from the test rig with rubber bands and springs.

e) The frequency of interest for comparison and correlation in this research is within 1500Hz for Normal Modes Analysis and EMA.

f) 1D element connectors are used in this study instead of 3D elements to represent the Hi-Loks in the assembled structure.

1.8 Thesis Outline

This thesis is divided into five chapters which are arranged in such a way that each topic develops logically in building a framework to analyse the dynamic behaviour of a Hi-Lok fastened structure experimentally as well as numerically.

In chapter 1, the background to the research, motivation, objectives, scope and significance of the study are presented. It also presents the structure and the methodology of the thesis.

Chapter 2 is a detailed literature review of the literature as far as structural dynamics, FE modelling of joints, and assembled structures, dynamic testing methodologies as well as past research results concerning Hi-Lok fasteners is concerned. The chapter defines main knowledge gaps and locates the present research in the big context.

Chapter 3 provides an in-depth account of the research methodology that entails the layout of the test structure, the preparation of EMA, FE modelling processes, and the model updating method. There are also equipments, software tools, boundary conditions, and element types discussed.

In chapter 4 the results of the experimental and the numerical analysis are given and discussed. It consists of a contrast in the natural frequencies and mode shapes, the assessment of the various FE modelling methods of the study, talk about the discussion of mesh convergence, and the results that came out of the undertaking of model updating. The present chapter demonstrates the strength of the suggested strategy of modelling and its confirmation using experimental data.

Chapter 5 concludes the study towards the conclusion of the study by summarising the major findings of the study, the contribution to the study and providing recommendations for future research of dynamic modelling of fastened aerospace structures in future.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The proposed literature review will seek to synthesis the current state of knowledge regarding the dynamic behaviour of Hi-Lok fastened structures. It has the following structure: Section 2.2 embodies introduction to the fundamentals of structural dynamics; Section 2.3 discusses modelling approaches to substructures, assembled systems, joints and matching interfaces; Section 2.4 is devoted to prediction of structural dynamics within normal modes and FRF; Section 2.5 describes techniques of modal updating; and Section 2.6 reviews experimentation in modal analysis. This systematic way of reviewing points out major problems, recent solutions, and weaknesses to Hi-Lok fastened assemblies modelling and analysis subjected to dynamic loading.

2.2 Structural Dynamics

The dynamics of structures is the study of the response of structures to dynamic loads i.e. forces or loads that are time-varying. The basic parameters that determine dynamic behaviour are natural frequencies, damping ratios and mode shapes. Such parameters are of special concern to the aerospace field where even the slightest resonance or dynamic instability may result in structural fatigue or failure.

Dynamic equation of motion in a linear system is usually expressed as:

$$Mx(t)+Cx(t) + Kx(t) = F(t) \tag{2.1}$$

with M, C, and K representing mass, damping and stiffness matrices respectively, x(t) representing displacement vector and F(t) being a time-varying driving force. In the case of assembled structures with fasteners the equation is complicated by the added localised flexibility and energy dissipation at the joints [42].

Some studies demonstrated that mechanical joints play a big role in world structure as they change stiffness adding nonlinear damping properties [43], [44]. In bolts and other joints, and in Hi-Lok fastened assemblies, the contact interface, preload conditions, and surface roughness all have an influence upon the modal behaviour of the whole systems [45], [46]. As an example, frequency shift and damping behaviour may come about through loading variation and this makes modelling and prediction to be consistent [47], [48].

Moreover, dynamic behaviour of both individual substructures and fully assembled systems may vary dramatically. It is more intensified in Hi-Lok fastened structures where the stiffness of the joint is very much dependant on installation, which is controlled by the use of torque and interface frictional forces. This means that the behaviour of substructure and interface dynamics would be required to characterise them in a predictable manner to predict full systems [49], [50].

Experimental results and computer-based modelling examinations remain to indicate that, just as resonance avoidance and fatigue life determination are vital to the joint dynamics of aerospace fuselage and wing assemblies in high load and high frequency conditions [51], [52]. The structural dynamics thus constitutes the level of analysis upon which the rest of the studies on joint modelling, modal tests, and updating is carried in the next sections.

2.3 Modelling of Structural Dynamics

The term modelling used in this section takes into account as the FE modelling used in predicting the dynamic behaviour of Hi-Lok fastened structures. To be able to predict how the assembled structures behave during dynamic loading accurately, structural modelling should be done properly. Joints, interfaces and material properties as well as boundary conditions should be considered in the modelling process and it will affect modal parameters and response of the system. With Hi-Lok fastened structures these considerations are more important especially because of the nature of the fasteners and the high significance of the fasteners in transferring load.

2.3.1 Modelling of Substructures

Substructuring requires dividing of a complicated structure into a set of simpler ones (known as substructures), e.g. Substructure A and Substructure B. In practice, each of these substructures is individually modelled and analysed before they are assembled to form a full system. Each substructure is characterized by local stiffness, mass and damping. In Hi-Lok fastened assemblies, substructuring can be particularly valuable when modelling the effect of individual components [53], [54]. The approach enhances efficient computation and gives a possibility to model the joints in detail at the interface resolution.

Component mode synthesis (CMS) is usually applied in substructure models to maintain key dynamic behaviour at a lower complexity of the model. The CMS methods assist in dynamic coupling on the interface, so that an accurate simulation of a jointed behaviour can be performed. When used on aerospace assemblies, this has worked well to determine mode localisation and estimation of energy damping as a result of joint flexibility [55], [56].

2.3.2 Modelling of Assembled Structure

After defining substructures, the global system is made by enforcing suitable connection constraints and interface representations. For bolted and Hi-Lok fastened assemblies, these formulations must account for preload influences, frictional contact and micro-slip phenomena [57], [58]. Realistic joint modelling assumptions are therefore essential to ensure that the FE dynamic model of assembled structures accurately represent the physical model.

Assembled structures may be modelled using FEM which typically include model elements of contact to depict the interplay between elements. Interface elements (zero thickness or cohesive zone elements) can also be introduced wherever sophisticated solution is needed to model separation and stick-slips transition at the joint [59], [60]. It has been found that correlation between numerical predictions and experimental modal data is better when joint behaviour is modelled realistically [61], [62].

2.3.3 Modelling of Bolted Joints

Bolted joints also provide local compliance and energy loss: both issues influence the overall dynamic response. To model such joints well, preload, friction, joint shape, and surface roughness effects must be appropriately represented. To address these requirements, a variety of elements are available in FE commercial software packages for modelling bolted joints. Among these, 1D elements such as CBAR, CBEAM, and RBE2 elements are commonly used to represent bolted joints. In this study, the Hi-Lok fasteners are represented using both one-dimensional elements (CBAR or CBEAM) and solid elements in order to represent the Hi-Lok fasteners as detailed as possible but required to achieve the desired computational efficiency. RBE2 elements are mainly deployed to simulate software constrictions among head or collars of the bolts and the structure. Typical methods are the incorporation of nonlinear contact elements, multi-point point constraints and approximations to the stiffness matrix [63], [64].

There are more difficulties with Hi-Lok fasteners because of its mechanism of installation, which is called a collar, as well as consistent preloading features of fasteners. One of the studies has constructed parametric models and experimentally validated them to enhance dynamic representation of joints to Hi-Lok [65], [66]. Such models frequently incorporate preload calibration, interface damping and bolt-hole clearance.

System-level simulations are occasionally performed with simpler models, e.g. spring and damper systems. These are however usually revised with the use of experimental data with the aim of taking account of joint behaviour. Combined analyses using EMA with FEM updating are very successful hybrid methods that have been used in modelling bolted and Hi-Lok joints, particularly in the aerospace sector [67], [68]. These modelling strategies are a wide area on which the issue of proper models of Hi-Lok fasteners are adopted in structural modelling.

2.3.4 Modelling of Interfaces

Previous studies have demonstrated that interfaces in jointed structure are the main cause of damping and nonlinear stiffness when subjected to dynamic loads. The interfaces of such systems are modelled through the simulated stick slip process and micro slip effects at the point of contact as well as frictional energy loss. An interface modelling is common in thin-layer elements, cohesive zone models, and in the surface-based contact method [69], [70].

In addition to contact behaviour, the type and size of meshing at interface are also very important to determine the simulation accuracy and numerical efficiency. Accurately representing stress gradients, and small-scale slip phenomena requires finer meshes, at the expense of computation time. Increased mesh size can create a simplification of contact behaviour and low estimation of variation of stiffness.

Tetrahedral elements are widely used, and hexahedral ones, but they perform poorly in the local geometry, as well as within the solver capabilities. This is because different types of the meshing and different mesh sizes were tested in the study in order to generate the most effective combination that could capture the dynamics of the Hi-Lok interface correctly.

The presence of Hi-Lok fastened in an assembled structure, interface behaviour is also dependent on the installation torque together with material combinations (e.g. metal to composite). These conditions need to be modelled accurately to obtain realistic expectation of dynamic response [71], [72]. Numerical experiments have revealed that the accuracy of FRF and mode shape prediction can be very highly enhanced by the consideration of detailed interface behaviour.

Hi-Lok fasteners are also more difficult because of the collar-based method required to install them and their steady behaviour of preload. Different modelling techniques are advanced to model fasteners in FE analysis. As an example, connectors axial and bending stiff properties may be simulated with CBAR and CBEAM elements, which bear less cost in computational effort than full 3D solid elements. RBE 2 elements are frequently used where rigid connectivity is required especially in applications where the geometry is not as important. The reasoning behind the trade-offs of simpler and more detailed representations has been discussed in sources like [84], [85] and [107]. Although 3D models with detailed representation of contact nonlinearities and localized stress fields are better represented through detailed 3D models, these models consume far more computation resources. In the environment of aerospace applications that require many fasteners, simplified representations in terms of 1D elements can instead be used, as done in e.g. [115]. To enhance the dynamic modelling of Hi-Lok joints, some studies have formulated parameters and checked them by an experiment [65], [66]. These are usually with preload calibration, interface damping effects and bolt-hole clearance.

Altogether, the realistic dynamic behaviour of the Hi-Lok fastened structures can only be attained through their effective modelling at substructures, assembled configurations, joint, and interface levels addressing the significant effects of the deformation rates at these levels.

2.4 Prediction of Structural Dynamics

Structural dynamics prediction is very important when it comes to analysing the behaviour of structure when exposed to different frequencies and excitation type. Some of the most basic tools which are applied in the context are normal mode analysis or FRFs. Such analyses can give an insight on the vibrational behaviour of structures and enable precautionary structural design changes in reducing resonance induced failures, particularly to jointed structures such as those employing Hi-Lok fasteners.

2.4.1 Normal Modes

Normal mode analysis is a method used to find natural frequencies and the mode shapes of a structure. These are the parameters of the natural overall vibration of a structure that does not have damping and external excitation. High stiffness joints, interface friction and contact condition play a key role in normal mode in structures when Hi-Lok joints are involved [73], [74]. Deviations small as compared to overall joint preload or surface conditions may produce apparent changes in natural frequencies or even the occurrence of localised mode shapes [75], [76].

The likes of noise control, fatigue evaluation and certification are some of the areas where determining these modal parameters are critical in the aerospace applications. It has been shown in a number of works that variations on the representation of joints may result into great differences between the predicted and actual properties of the modalities [77], [78]. Therefore, modal validation by high-fidelity modelling and analysis of modal characteristics, together with subsequent experimental verification is routine practice when considering Hi-Lok fastened components.

2.4.2 Frequency Response Function

FRFs are frequency domain representations of the steady-state response of a structure to harmonic excitation and are popular for identification and analysis of the dynamic response of the structure such as natural frequencies, damping and mode shapes. A FRF describes the behaviour of input forces (at a range of frequencies) and resulting displacements, velocities, or accelerations found at certain points of the structure. This information is especially important for identifying nonlinearity behaviour, local flexibility and damping effect added by joints [79], [80].

In the case of Hi-Lok fastened structures, FRFs can further show changes in the dynamics of the system arising from bolt loosening, loss of preload, or due to the wear of the structure. In addition, FRFs are widely used as critical inputs associated with FE updating model and the structural health monitoring system [81], [82]. Both simulation and experimental studies have shown that the FRFs of conventional bolted joints are often unstable and difficult to represent, whereas Hi-Lok joints whose consistent preload mechanisms, exhibit more stable and predictable FRF characteristics [83], [84].

Finally, use of both normal mode analysis and FRF assessment divulges a complete overview of dynamic behaviour of a structure. These forecasting tools provide the basis of model verification and revision as well as vibration control measures throughout Hi-Lok fastened assembly.

2.5 Modal Updating of Structural Dynamics

FE models tend to not match well with experimental data because simplifications, parameter uncertainty, or unmodelled boundaries were made. One lessens this gap through modal updating techniques by finer tuning numerical models with experimental data. Such methods make the predicted dynamic responses more accurate and increase confidence on simulations of Hi-Lok fastened structures.

2.5.1 Modal Based Updating

The aim of modal-based updating is to correlate well the predicted and experimental modal properties such as natural frequencies and mode shapes. Typical methods are sensitivity updates, least squares fits and matrix corrections [85], [86].

Stiffness and damping characteristics in jointed structures, in particular those where Hi-Lok fasteners are used, usually are the primary factors contributing to the modelling error. Within the scope of this study, a modal-based updating approach is adopted, with particular emphasis on variations in material properties such as Young modulus, density and Poisson ratio. Misjudged assumptions about material stiffness, distribution of mass and damping coefficients may induce serious differences between simulation and experimental comparisons [87], [88].

In addition to jointed stiffness and damping effects, the properties of materials are also predominant in the determination of dynamic response of Hi-Lok fastened assemblies. Variations in alloy composition, manufacturing processes, and composite layups can lead to significant differences in modal characteristics, even when the overall geometry and fastener configuration remain unchanged. Thus, the material properties such as Young modulus and other material proprieties, like density and loss factor, must be correctly updated to improve the accuracy of the predicted responses [89].

Researchers have shown that where material property identification is included in the updating procedure, an improved fit to test data can be achieved especially where joint effects are secondarily fixed or calibrated independently. These methods are mostly categorized into the following, sensitivity-based techniques, response surface techniques and direct matrix updates. An output gradient on some uncertain parameters (such as material properties) lies behind sensitivity-based methods, and one can observe that this approach was adopted in the present study. Examples of results of studies of such kind include [49], [50], and [81], whose findings have demonstrated that the approach provides a reasonable trade-off between accuracy and computational expense. In comparison the direct schemes such as those described in [13] and [14] are more rigorous but can be sensitive to noise and may be not robust. Technical tools such as FEMtools and Nastran were also available to give convenient structures that could be followed in the effective implementation of the strategies. Even though they vary, all the methods strive to reduce test and FE data error, which normally result in cost functions depending on differences in frequencies or MAC values. This will prevent the overcompensation in joint modelling and will place emphasis into the parameters that are of the most significant influence in the structural dynamics. Also, parameterised models under the flexibility of variable material stiffness and damping are more flexible in the updating process. To reduce the difference between testing results and analysis ones, iterative algorithms and methods of optimisation are usually utilised [90], [91].

Moreover, more flexibility during updating process is given by the use of parameterised simpler models where interface stiffness, contact area and damping ratios can be varied. Similar strategies are usually applied to the test and results of analysis, as iterative algorithms and optimisation procedures are used to minimise the difference between the test and the analysis [90], [91]. Considering that it is a proven method with a good balance between computational cost and the accuracy of the results, the sensitivity-based approach is utilized in the proposed study.

2.5.2 FRF Based Updating

The FRF-based updating technique improves FE models by directly using the measured FRFs rather than relying on modal parameters extracted from modal data. This approach is particularly suitable for structures for which modal identification is difficult, such as systems exhibiting closely spaced modes, high damping levels, or complex damping behaviour that does not follow simple assumptions. These characteristics are commonly observed in Hi-Lok fastened joints, making FRF-based updating a more reliable method for refining the FE model in such applications [92], [93].

The current FRF based updating normally entails relating a purposeful capacity, measuring the distinction of measured and computed FRFs. This is then optimised under some optimisation methods like genetic algorithms, gradient-based solvers, or response surface methods [94], [95].

Research has demonstrated that FRF based updating can register the minor modification of the joint characteristics as a result of preload loss, interface deterioration or fastener wear [96], [97]. Consequently, it is predominantly installed in structural health monitoring and damage detection projects based on complicated joined systems.

Conclusively, modal and FRF based updating methods present very useful tools of enriching the performance of dynamic models. The application of these methods to Hi-Lok fastened structures allows improved predictive capacity; therefore, more sensible design and analysis of aircraft parts in the condition of motion.

2.6 EMA of Structural Dynamics

In order to validate analytical and numerical models of structural dynamical models, EMA is imperative. It is the technique of extracting parameters, including natural frequencies and damping ratios and modes shapes in physical structures by controlled excitation and measurements of response. In jointed systems, EMA is particularly significant because near interface properties in modelling can oversimplify the true situation. With a stable preload and the configuration associated with Hi-Lok fastened structures, it is quite advantageous to EMA to sense joint stiffness, damping behaviour, and fastener performance in assembled structures [98].

EMA is mostly done within the boundaries of operation to achieve real-life dynamic responses. This process becomes more accurate depending on the type of excitation, how far the sensors are positioned and what signal processing techniques are applied to acquire the FRFs [99], [100].

2.6.1 Impact Hammer

The impact hammer method is a simple and portable experimental technique and is therefore one of researchers' favourite approaches for EMA. It involves exciting a structure with an instrumented hammer, and measurement of the resulting acceleration response. It is a perfect means of identifying modal parameters at early stages and formal systems that possess simple, low-frequency modes [101], [102]. Nevertheless, it might not be so efficient in higher frequencies or in highly damped structures, where energy is finite, and not constant.

Hammer testing is a convenient method of identifying global modal behaviour in Hi-Lok fastened structures, but it is not likely to be as sensitive to fine nonlinearities or elaborate joint behaviour as can be achieved using shakers [103].

2.6.2 Shaker

The shaker-based excitation provides variable input on a wide frequency range continuously. It is frequently deployed in the high-resolution test, applicable especially in the detection of closely spaced modes or high-damping behaviour [104]. In the case of Hi-Lok fastened structures, shaker testing can be successfully used to consider the stiffness at the frequency and damping behaviour of joint when interpreting interfaces between composite and metals [105].

Depending on the force range and size of structure, the electrodynamic or hydraulic shakers can be employed. Shaker methods by maintaining force control and instrumentation allow one to gather the modal properties which are both global and local in accurate ways.

2.6.3 Excitation

The choice of excitation method such as impact, shaker or random input depends on the number of responses to be measured, and the structural complexity under investigation. For Hi-Lok fastened assembled structure, it is essential to apply adequate excitation to ensure that sufficient energy is transmitted across the entire structure, particularly to modes affected by joint flexibility, bolt preload as well as interface slip. Consequently, multiple-point excitation has been employed in many studies in order to enhance observability in the mode shapes [106].

2.6.4 Measurement Nodes

The attachment of sensors is crucial for measuring the full dynamic behaviour of jointed structures. In particular, the regions around Hi-Lok joints are carefully selected for accelerometer attachment to effectively monitor local flexibility and identify joint nonlinearity [107]. The resolution of mode shapes and the accuracy of damping estimations are strongly influenced by both the number and placement of accelerometer at the measurement nodes.

A number of guidelines call to install sensors at antinodes of anticipated modes in order to optimise the response amplitudes and enhance the MAC in comparisons between mode shapes. Intricate structures can have spatial resolution enhanced by an advanced technique such as roving hammer, roving accelerometer or dense grid scanning.

In EMA for measuring the mode shapes a structure. the key distinction between the roving hammer and roving accelerometer methods lies in which instrument moves while the other stays at a fixed reference point. The roving hammer method involves moving an impact hammer to different points on the structure while a single accelerometer remains stationary at one location. This approach is generally considered more convenient and efficient for simple structures like beams, as it avoids the time-consuming process of repeatedly unmounting and remounting the accelerometer [2, 5].

Conversely, the roving accelerometer method keeps the impact hammer fixed at a single reference point and moves the accelerometer to various locations. This method can simplify the acquisition of a complete set of FRFs needed for a full 3D mode shape analysis because the input force is always applied at the same point and direction for all measurements [1, 4]. However, this method is more labour-intensive and may introduce "mass loading" effects, potentially altering the structure's dynamic properties, especially when testing small or lightweight objects [3].

Ultimately, both methods can yield the same theoretical results if the measurement approach is thorough and follows the principles of reciprocity, but careful consideration of the test setup is needed to ensure complete mode shape information is captured [2].

2.6.5 Boundary Conditions in EMA

Boundary conditions in EMA are the set of conditions that directly affect the modal characteristics. The type of boundary conditions that will be used in this study is two conditions which are free-free and free-hanging. The configurations are chosen where the dynamic behaviour of the structure is isolated and less artificial constraints introduced to distort the results.

Free-free conditions are basically unconstrained states and used to provide an insight of how a structure behaves naturally without external binding. This arrangement is created when the structure is suspended with elastic cords, foam blocks or soft springs in a manner which imitates a floating state [114]. It is most helpful in realizing the full set of global modes and also in the validation of numerical mode where the boundary constraints are not explicitly specified.

Free-hanging installations are put in place to reduce the constraint force yet maintaining the physical stability of structure. This would be feasible in large or odd shape test articles (particularly in aerospace). The structure can be suspended vertically or at certain support points in order to minimize boundary effects so as to be able to simulate more realistic conditions in-service [112].

Both systems work effectively when experiments are carried out on Hi-Lok fastened structures since they serve to bring out causes and effect of the fasteners on the dynamic response without disturbing the boundaries with artefacts. These boundary conditions should be well-implemented so that these can be consistent with FE models and also to improve the quality of the correlation and model updating processes [113].

2.7 Correlation Techniques

In structural dynamics, the correlation techniques can be used to evaluate and refine the correspondence between numerical and experimental models. They play a fundamental role in assessing the validity of models in FE, as it compares a model predicted outcome against those measured experimentally in modal parameters or FRFs.

The MAC, COMAC and Orthogonality Check are the most popular of them. The MAC measures the correlation between EMA and FE mode shapes, and the value approaches to one show perfect correlation. It is calculated with dot product of two mode shape vectors and gives out a value that lies between zero and one. The value of one identifies perfect correlation whereas zero is an utter orthogonality. MAC plays a significant role in the experimental practice to confirm the identity of modes shapes as analysed and experimentally identified. It can be especially helpful in complex jointed structures in which locally the mode shapes can deviate because of the joint flexibility or contact nonlinearity. In the case of Hi-Lok fastened structures, MAC values provide a quantitative measure for evaluating the accuracy of joint modelling by explicitly indicating mismatches in localised modal behaviour. The value of MAC in Hi-Lok fastened structures can vary a lot due to the manner in which the flexibility and damping of the joints have been modelled [114].

The other fundamental method pertains to the FRF correlation especially when implementing the FRF based model updating. A difference in amplitude and phase of FRF with frequency bands is used to determine a mismatch in either stiffness, damping or boundary conditions. The differences frequently are related to the joint properties, e.g. preload or friction with the contact [112], [113].

The recent development of advanced correlation methods merges modal and FRF data to give the strong indicators of model accuracy. There are methods that have objective functions that are based on the two sets of data and minimised in optimisation procedures to update models. Such methods are used when the validity of the predictive dynamic simulation performance needs to be increased when applied to Hi-Lok assemblies [114].

2.8 Concluding Remarks

This chapter has summarised the dynamic modelling, analysis as well as validation methodologies that may be used in relation to Hi-Lok fastened structure. It started with the presentation of basic foundations of dynamic structural analysis and further advanced to elaborate issues of the modelling approaches, predictive techniques and model updating schemes. EMA and correlation tools were also considered to implement their functionality to the field of verification and refinement of the simulation results.

The literature points out that Hi-Lok fasteners have unique dynamic behaviours, as their preload is always uniform and the device is installed in a specialised manner, so these variations need to be considered carefully during numerical models. The simplified joint representations can be used in preliminary analyses but there is need to have high fidelity modelling of joint interface, damping in materials and preload effects to have realistic dynamic prediction.

Some of these issues still have to be resolved such as a quantification of the joint damping and identification of preload-dependent changes in stiffness and scale able model alteration of intricate assemblies. Combined experimental, numerical methods will lend themselves to subsequent work with the aim of improving these models, as well as having greater faith in how they may be used to analyse high-performance aerospace structures.

This is an important gap in research by any standards unless one takes into account a large presence of Hi-Lok systems in aerospace structures nowadays. Moreover, the existing research either focuses on detailed 3D modelling or only on the experiments, omitting any organized comparison of several simplifications' strategies. The present research answers this question by comparing four of the FE methods used to model a Hi-Lok fastened structure and comparing each method to experimental modal data as well as comparing the methods in terms of accuracy and computational cost.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

The study of FE modelling and updating the dynamic behaviour of the structure with Hi-Lok fasteners is carried out in several phases. It includes the modelling of the substructures and the assembled structure, the measurement of their natural frequencies and mode shapes through Normal Modes Analysis and EMA, and the updating of the FE models to minimise the errors between FE and experimental results. This section describes in detail the methodology used in this study.

3.2 Research Design and Approach

This study is an analytical and experimental investigation aimed at developing a reliable, efficient and economical FE model capable of representing the dynamic behaviour of the assembled structure with Hi-Lok fasteners. In this study, an attempt is made to solve a structural dynamics problem using an established approach and theory. Therefore, the aim of this study is developed around the experimental and numerical analysis methods with reference to the theories of modal analysis and FE model updating.

The main data for this study are collected using EMA and normal modes analysis, both of which were used recently by other researchers [46], [50], [90]. Data collection is carried out in the laboratory where the experimental tools and test rig are set up. The substructures were fabricated in a machining shop using the design drawings. The same components were assembled as they are intended for the assembled structures.

The data, which consists of natural frequencies and mode shapes, is further analysed to provide the information required for MAC analysis. The analysis of the data and the FE model updating are carried out using the dedicated computer-based systems Simcenter TestLab and MSC PATRAN /NASTRAN for the data obtained from the experiment and numerical methods respectively. The results of the analyses are further evaluated for the comparison and visualisation of the results such as the total error and the sensitivity analysis.

Figure 3.1 illustrates the flow of research activities in this study. They are the analysis of the normal modes, EMA and FE model updating at two different levels, namely the substructure level and assembled structure level. At the substructure level, normal modes analysis and EMA are performed separately before the results of both methods are compared. The comparison determines the degree of correlation between the two results, which then leads to the need for the FE model updating to reduce uncertainty. Once the FE model updating is completed, the updated FE model is subjected to the normal modes analysis of the substructure, again comparing the result to the experimental counterpart. In case of uncorrelated or strongly deviating results, the FE model updating must be performed with a different setting of the updating parameters.

After the correlation result with the minimum total error between experimental and numerical analysis is satisfactory, the updated FE models of the substructures are used to form an assembled structure with Hi-Lok fasteners. The FE model of the assembled structure is subjected to normal modes analysis while EMA is performed for the physically built assembled structure. Both results are then compared to determine the degree of correlation and the value of the total error. The comparison process is the same as the process performed for the substructure. However, the difference is mainly in the parameters of the Hi-Lok fasteners, as the substructure errors are normally minimised before updating the assembled structure.

The total error resulting from the comparison between the normal modes analysis results and EMA of the assembled structure is reduced by the FE model updating. As explained earlier, the updated FE model of the assembled structure is again compared with its experimental counterpart. At this stage, a lower overall error of the updated FE model is expected, indicating that the selected updating parameters of the Hi-Lok fasteners are successfully updated with respect to the EMA data. The process ends at this stage where the updated FE model can be used for subsequent analysis.

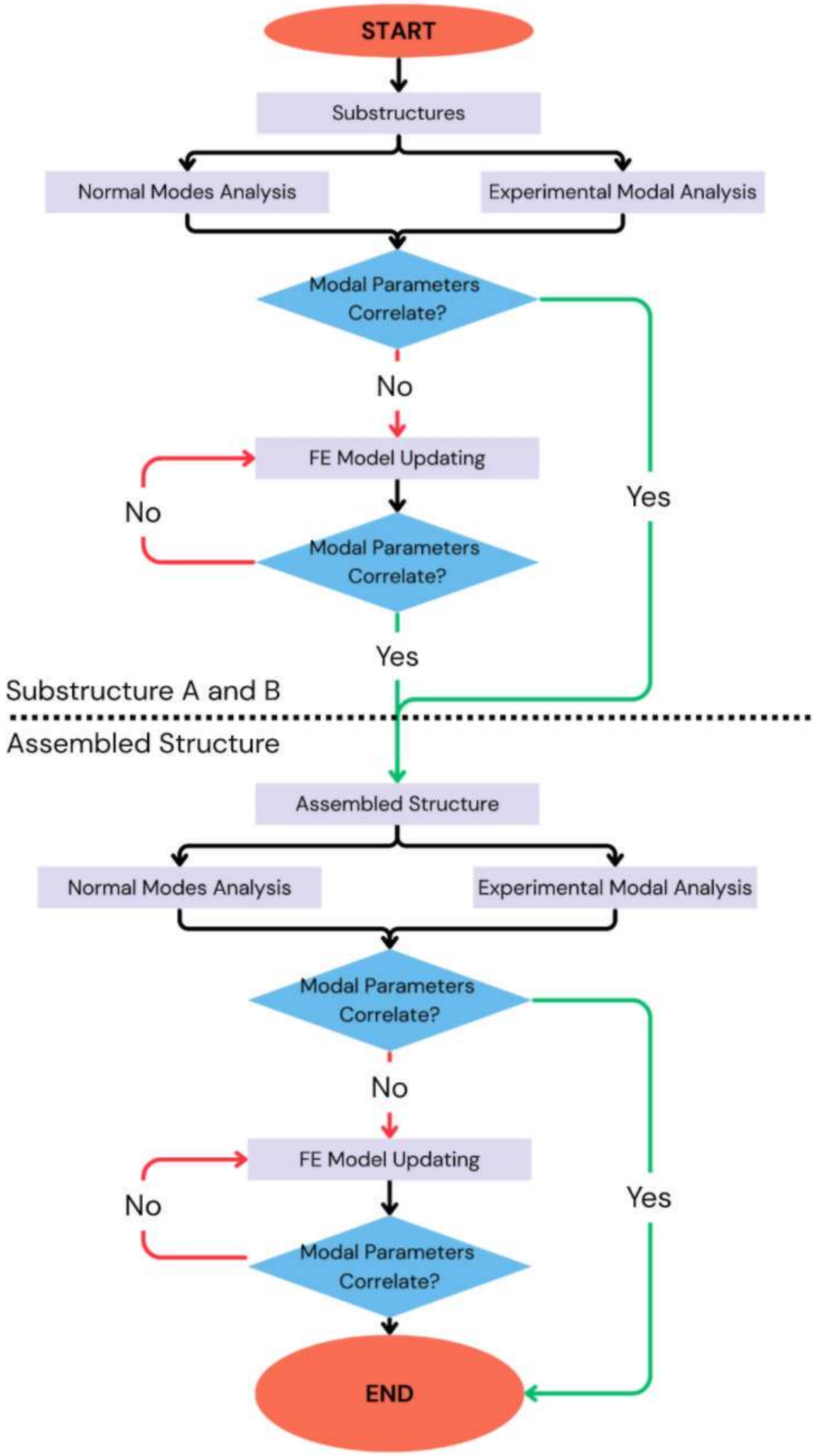


Figure 3.1 Flow of Research Activities for This Study

3.3 Overview of EMA

EMA was conducted to determine the natural frequencies, mode shapes as well as the damping ratios of the structure. The test arrangement was performed with Simcenter Testlab Impact Testing software combined with a Simcenter SCADAS data acquisition component (Plate 3.1) where measurements could be conducted synchronously and the progression of FRF was in real time.

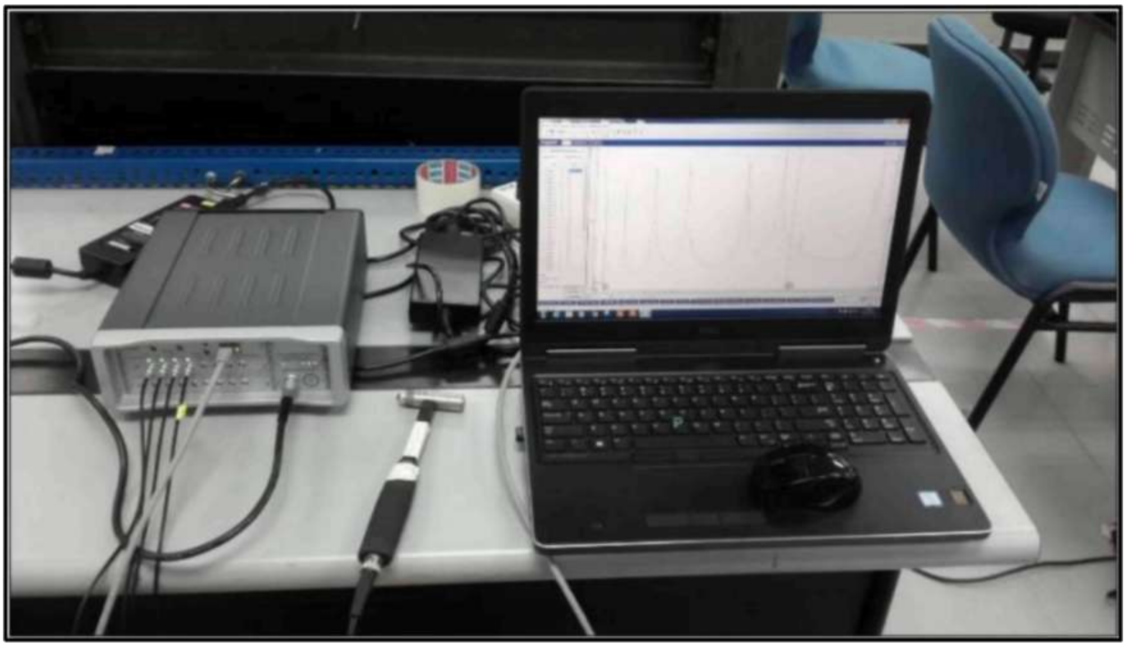


Plate 3.1 Simcenter Testlab Impact Testing Software on a Laptop and Simcenter Scadas Data Acquisition

An impact hammer (PCB 086C02) as shown in Plate 3.2 was used to excite the structure controlled impulse forces at specifically assigned nodes. Dynamic behaviour of the structure was measured with three monoaxial accelerometers (MMF KS91C) as shown in Plate 3.3. The accelerometers were carefully attached in order to measure the vibration in the x and y directions at important locations of the test structure.

Plate 3.2 Impact Hammer Used in Testing

Plate 3.3 Accelerometers Used in Testing

Measurements were acquired at a sampling rate of 2048Hz. The frequency range of interest was limited to 0 - 1000 Hz, because the targeted modes of the test structure were expected to occur within this frequency range. Appropriate windowing techniques and anti-aliasing filtering were used to ensure accurate estimation in the selected frequency range. The HI estimator was used to calculate the FRFs as it provides robust estimation where the response measurements are more affected by noise than the input force, which is typically the case in impact hammer testing using accelerometers. A total of 18 measurement nodes were chosen on the structure to ensure sufficient spatial resolution for accurate the mode shape identification.

Synthesis of modal parameters was performed with modal parameter estimation tools in Simcenter Testlab, in case of initial estimates, Peak Picking was used, and then the PolyMAX curving tools were used. The obtained mode shapes and frequencies were confirmed by the coherence analysis and repeatability under a wide range of measurement settings.

3.4 Overview of FEM

In this study, the dynamic properties of the test structure were predicted using the FE model developed. To evaluate the accuracy of the FE model, the predicted results are compared with their EMA counterparts. The FE modelling work was carried out using Altair HyperMesh, MSC Patran, and MSC Nastran.

FE mesh generation was carried out using Altair HyperMesh where there was a mix of 2D shell elements and 3D solid elements in the model. Thin plate-like regions where the thickness is small in comparison with in-plane dimensions were modelled using shell elements, while the solid elements were assigned to the regions where the representation needs to be three-dimensional and the through-thickness effects have an influence on the stiffness distribution. Mesh refinement was performed to reach the element size of 5 mm while still keeping the computational cost at a reasonable amount. Mesh convergence was confirmed by observing the stabilisation of the first few natural frequencies for decreasing element size. The mesh details with number of elements and nodes using each of the modelling techniques is summarised in Table 3.1.

The meshed model was next translated to MSC Patran which acted as pre-processing system of assignment of material property, boundary condition and analysis parameterization. It was assumed that the material behaviour was linear, homogeneous, and isotropic, which is also standard when it comes to the modal analysis. The FE boundary conditions were set as free-free to mimic the EMA set-up using rubber bands and springs to suspend the test structure. In this case, no translational and rotational restriction constraints were imposed in the Normal Modes Analysis.

Modal analysis was conducted by using MSC Nastran Solution 103 (Normal Modes Extraction) used to compute the undamped natural frequencies and its corresponding mode shapes. The FE and EMA analysis represent free vibration, and thus no external loads were applied. The natural frequencies and eigenvectors that resulted out of the FEM simulation were subsequently compared to the experimentally identified modal parameters used in validation and cross-correlation.

Table 3.1
Detailed Information on the Four FE Models of Hi-Lok Fasteners

Detail	Technique 1	Technique 2	Technique 3	Technique 4
Type of Element (Substructures A & B)	3D CTETRA4	3D CTETRA4	2D CQUAD4	2D CQUAD4 + CTRIA3
Type of Element (Hi-Lok)	None	3D CTETRA4	1D RBE2-CBAR	1D RBE2 Spider
Number of Elements	14642	451507	19654	1214
Number of Nodes	3869	96091	4990	1361

3.5 Overview of Model Updating

Model updating is performed with the purpose of achieving a better agreement between experimentally obtained modal parameters and FE model. Despite careful initial modelling, apparent differences in natural frequencies and mode shapes inevitably remain due to uncertainties in material properties, boundary conditions, and geometric simplifications. To address these discrepancies, updating process was carried out via FEMTools, with the objective of improving the accuracy and robustness of the FE model predictions.

In this study, model updating was carried out. with the purpose of varying selected material properties, namely the Young's modulus, the Poisson's ratio, and the mass density, because these parameters were observed to have a strong influence on the predicted modal characteristics. These parameters were chosen as updating parameters because the natural frequencies and mode shapes were sensitive to them.

The updating procedure was guided by two correlation parameters: percentage error in natural frequencies and the MAC that can be used to compare the experimental and numerical mode shapes. In this study acceptable frequency discrepancy of < 5% was targeted while MAC value > 0.90 and above was considered to be in good agreement. The final updated model showed the demonstration of the better correlation with the experimental results and therefore was suitable for further analysis and predictive purposes.

3.6 EMA of the Substructure

Before performing experimental tests on the assembled Hi-Lok fastened structure, EMA was performed initially on individual substructures (Substructure A and Substructure B) in order to determine their baseline dynamic properties. The experimentally identified natural frequencies and mode shapes of the substructures were taken as reference data for the validation of the FE models of the individual components and for the interpretation of changes of dynamic behaviour after the assembly.

Both substructures were built using Aluminium 7075 alloy, which was chosen because of its very broad use in aerospace structural applications and its favourable strength to weight ratio. The test specimens included flat rectangular plates with through holes located at the joint interface to be covered by the Hi-Lok fasteners. The detailed dimensions and the geometric configuration of Substructure A and Substructure B are in Figure 3.2 and Figure 3.3 respectively. Tolerances in fabrication and surface finishing were also carefully controlled to reduce geometric variations, which can cause changes in contacts condition and dynamic response.

In order to approximate to free-free boundary conditions during EMA, each substructure was suspended by rubber bands and threads. This suspension method was adopted as it adds minimal stiffness and damping to the system and therefore the measured dynamic response of the system is close to the inherent modal behaviour of the structure under free-free conditions.

The structures were excited with an instrumented impact hammer (PCB 086C02) and the roving accelerometer technique with varying excitation location and fixed response transducers was used. For the tests of the substructure, a total of 10 measurement points (nodes) were referred to represent the mode shapes adequately as shown in Figures 3.4. The points of measurement were distributed to represent the global patterns of deformation of the dominant modes and to avoid being placed at expected nodal lines.

Following the substructure tests, EMA was performed on the assembled Hi-Lok fastened structure following the same approach of measurement to achieve consistency. For the assembled configuration, 18 measurement points (nodes) were chosen to have a good spatial resolution in order to obtain a good identification of the global bending and torsional modes in the structure. The structure of the measurement point plan for the assembled structure is shown in Figure 3.5.

Accelerometers (MMF KS91C) were positioned at suitable positions to obtain measurable amplitudes of response and different impact excitations were carried out at each measuring position to ensure repeatability and minimize the contribution of random measuring noise. Data acquisition and processing was performed using Simcenter Testlab in conjunction with the Simcenter SCADAS system. The FRFs were computed using the H1 estimator, because it provides reliable results for the FRFs when the response measurements are more subject to the noise than the input force as usually is the case during impact hammer testing.

Modal parameter extraction was carried out following the PolyMAX algorithm which was chosen because of its capability to accurately identify closely separated modes and stable modal parameter extraction in the presence of measurement noise. The extracted modal parameters were verified using the coherence and repeatability. Such experimentally identified modal parameters were then employed for FE model validation purposes, and also for model updating processes as explained in the next sections.

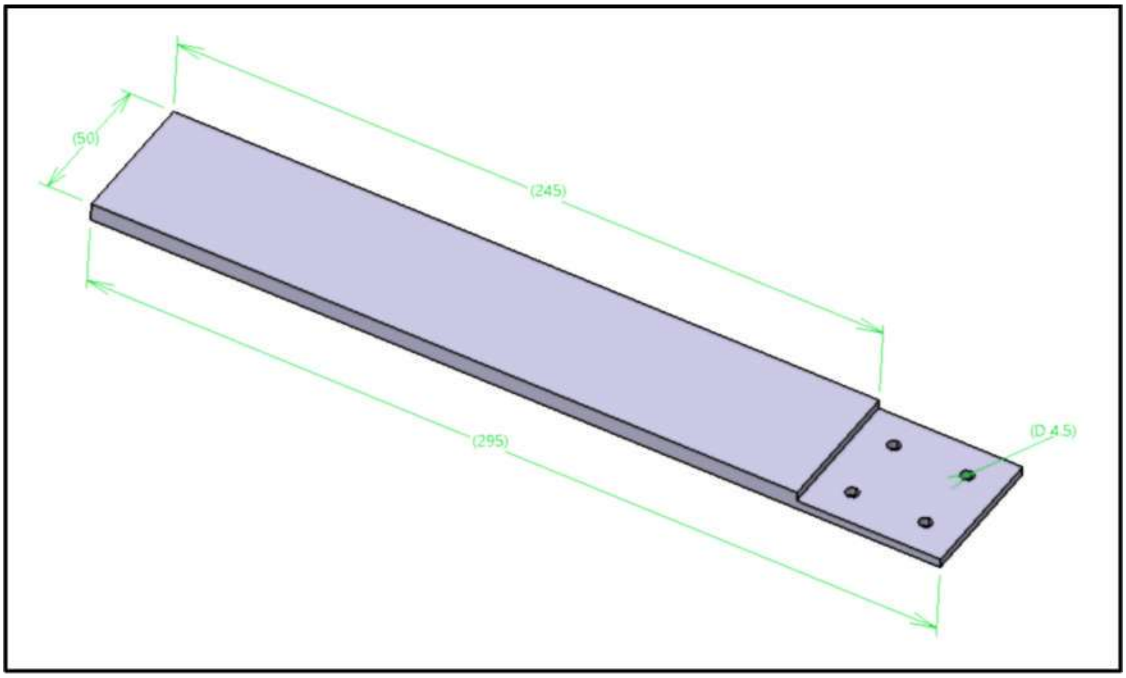


Figure 3.2 Detailed Dimensions for Substructure A and B

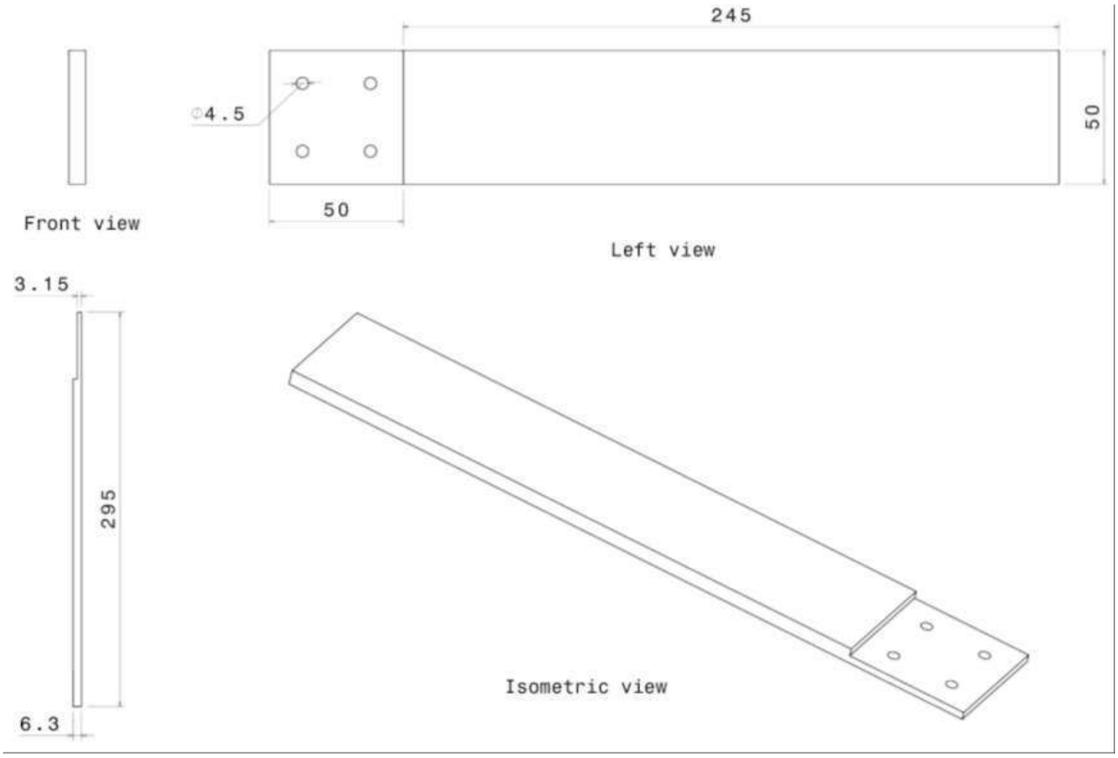


Figure 3.3 Isometric Drawing for Substructure A and B

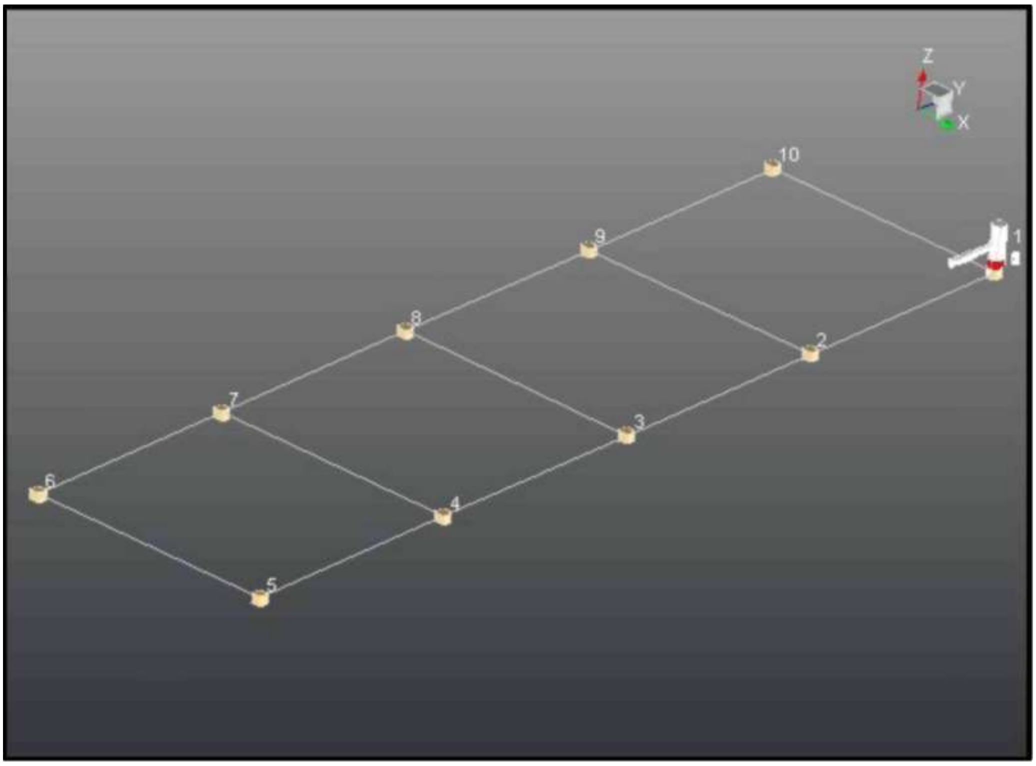


Figure 3.4 Measurement Points (Nodes) Layout for EMA of the Substructure (10 Points)

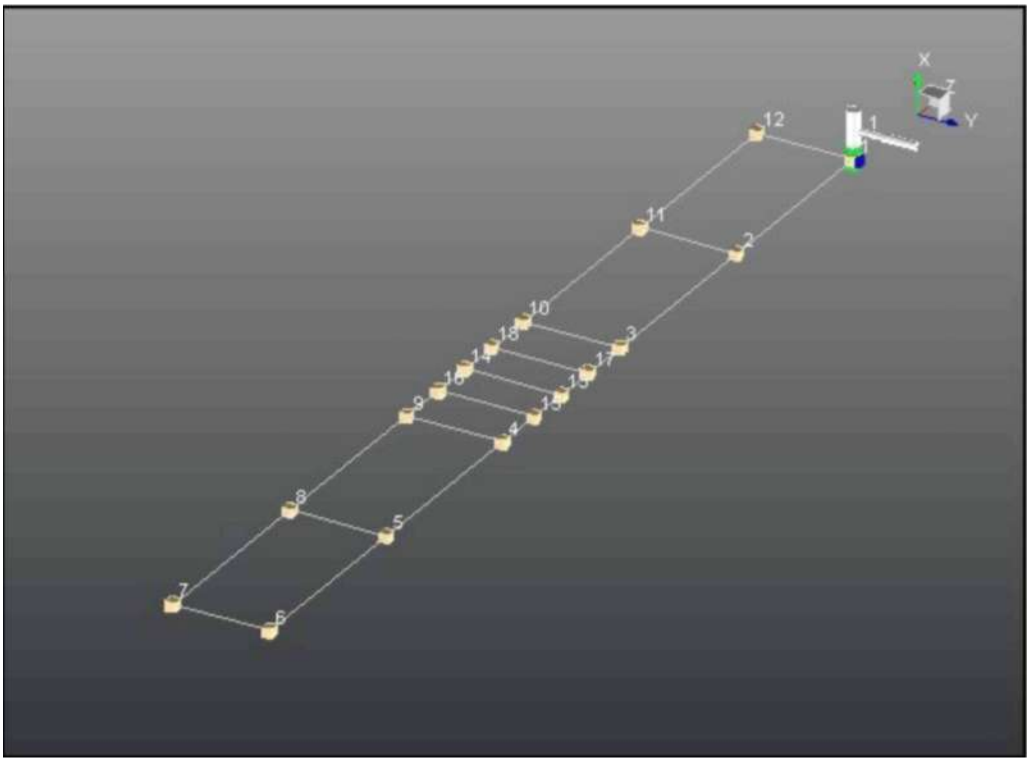


Figure 3.5 Measurement Points (Nodes) Layout for EMA of the Assembled Hi-Lok Fastened Structure (18 Points)

3.7 EMA of the Assembled Structure

Experimental investigations typically provide robust information about dynamic behaviour of assembled structures [6, 15]. In the present investigation, the assembled structure was made of two identical aluminium 7075 substructure joined together with alloy steel Hi-Lok pins and aluminium Hi-Lok collars. The general geometry and size of assembled are shown in Figure 3.6 to 3.7.

EMA was performed on the assembled structure to measure the natural frequencies and mode shapes of the structure. The measured results were then used for further comparison with FE analysis predictions to assess the effect of the Hi-Lok fasteners on the global dynamic behaviour. The testing was done with Simcenter Testlab for the impact testing coupled with the Simcenter SCADAS data acquisition system, an instrumented impact hammer, and three accelerometers.

To approximate free-free boundary conditions, the assembled structure was suspended from a test rig with rubber bands and threads. The roving hammer method was used, and 18 measurement points (nodes) were defined on the assembled structure as shown in Figure 3.5 in order to have a sufficient spatial resolution to identify the global bending and torsional modes. The schematic representation of the experimental set up and instrumentation for the impact test is shown in sections 3.7.1 to 3.7.3.

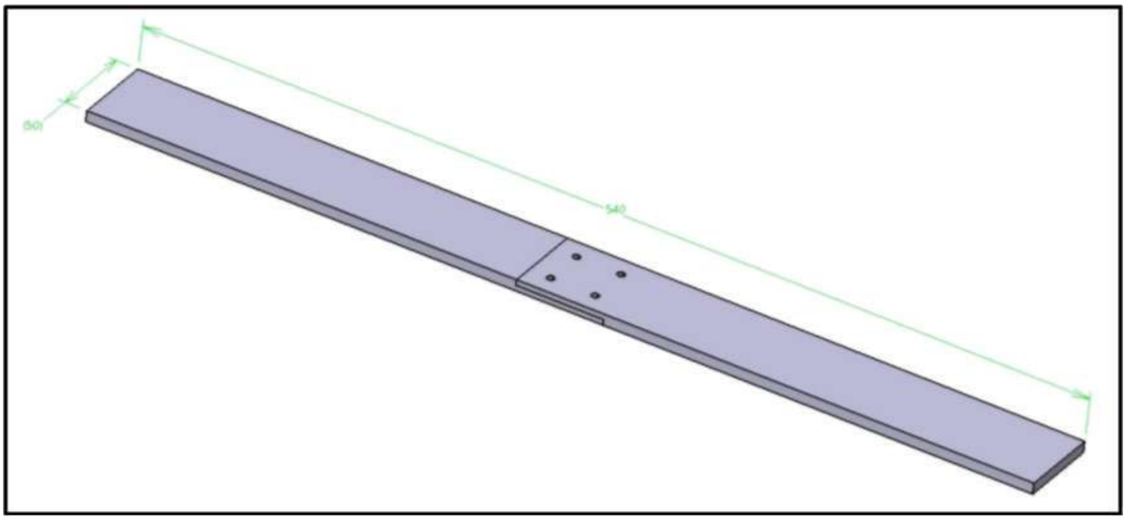


Figure 3.6 Detailed Dimensions for Assembled Structure

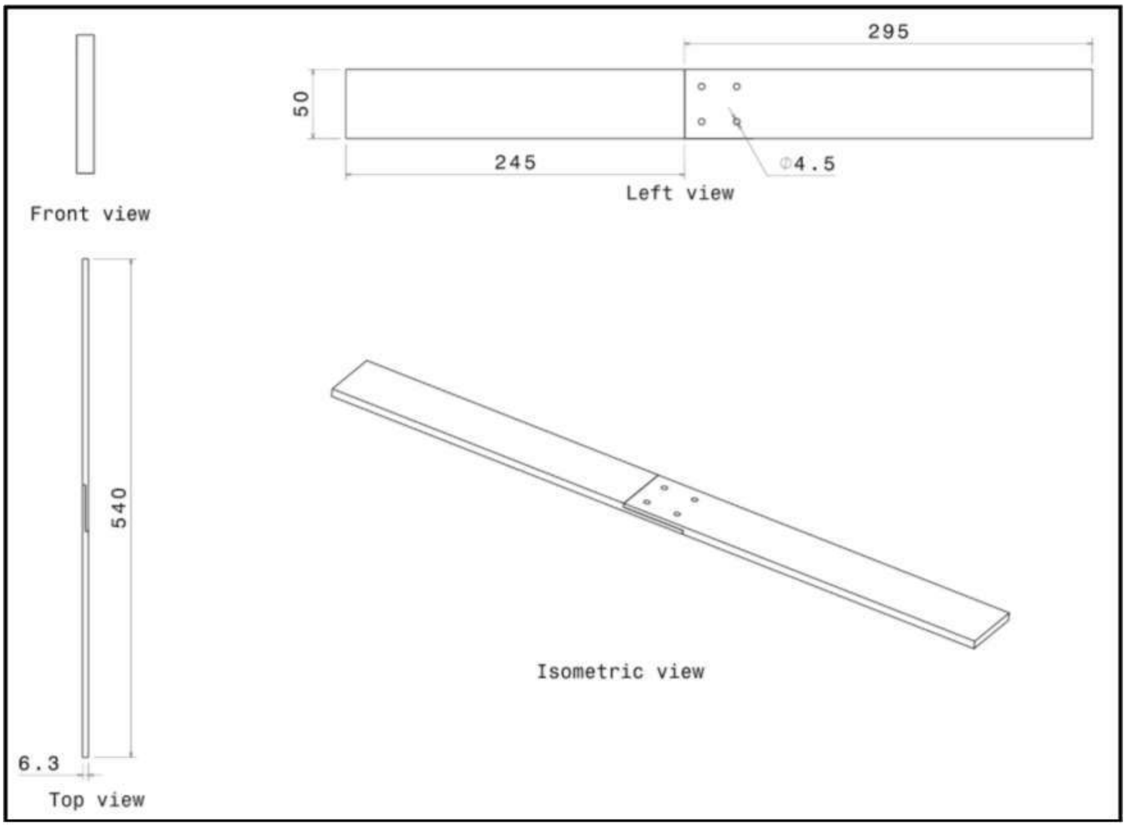


Figure 3.7 Isometric Drawing for Assembled Structure

3.7.1 Vertical

The first EMA set-up, the assembled structure was a vertical position using two rubber bands with springs joined at one end as shown in Figure 3.8. This vertical suspension configuration was chosen to (i) approximate free-free boundary conditions, and (ii) test the gravitational effects on the measured dynamic response. Although gravity cannot be completely eliminated in practical testing, the use of flexible rubber bands and springs minimises external constraint and the structure can vibrate in largely its natural modes.

For this configuration excitation was applied using an instrumented impact hammer in vertical, out-of-plane direction, and accelerometers were oriented to measure the vertical out-of-plane response. The excitation and the placement of the sensors were selected to minimise the signal-to-noise ratio and to ensure that the measured FRFs enabled reliable identification of the mode shapes.

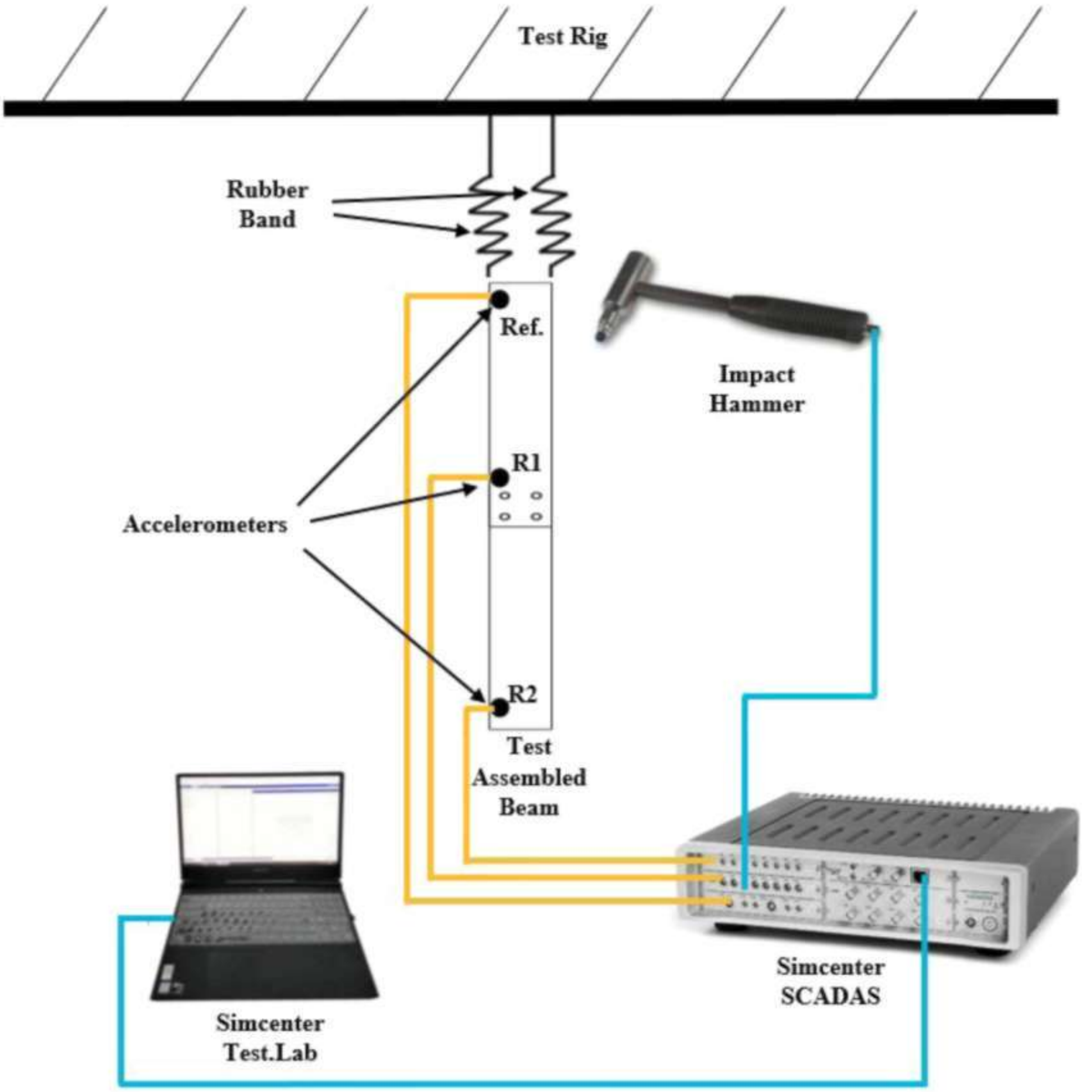


Figure 3.8 Schematic Diagram of EMA for Vertical Direction

3.7.2 Horizontal

In the second setup, the assembled structure was suspended in the horizontal orientation by four rubber bands and springs, with both ends attached at the edges of the test rig, as can be seen in Figure 3.9. This symmetric suspension configuration was used, allowing a stable and repeatable configuration while minimising external constraint and thus to approximate free living (free - free boundary conditions) more closely. The combination flexibility of the rubber bands and the springs diminished the stiffness that was created by the support system and enabled the structure to vibrate mostly in its natural modes.

For this case, excitation was delivered by an instrumented impact hammer in the out-of-plane direction, the accelerometers were directed to measure the associated response at the prescribed measurement nodes.

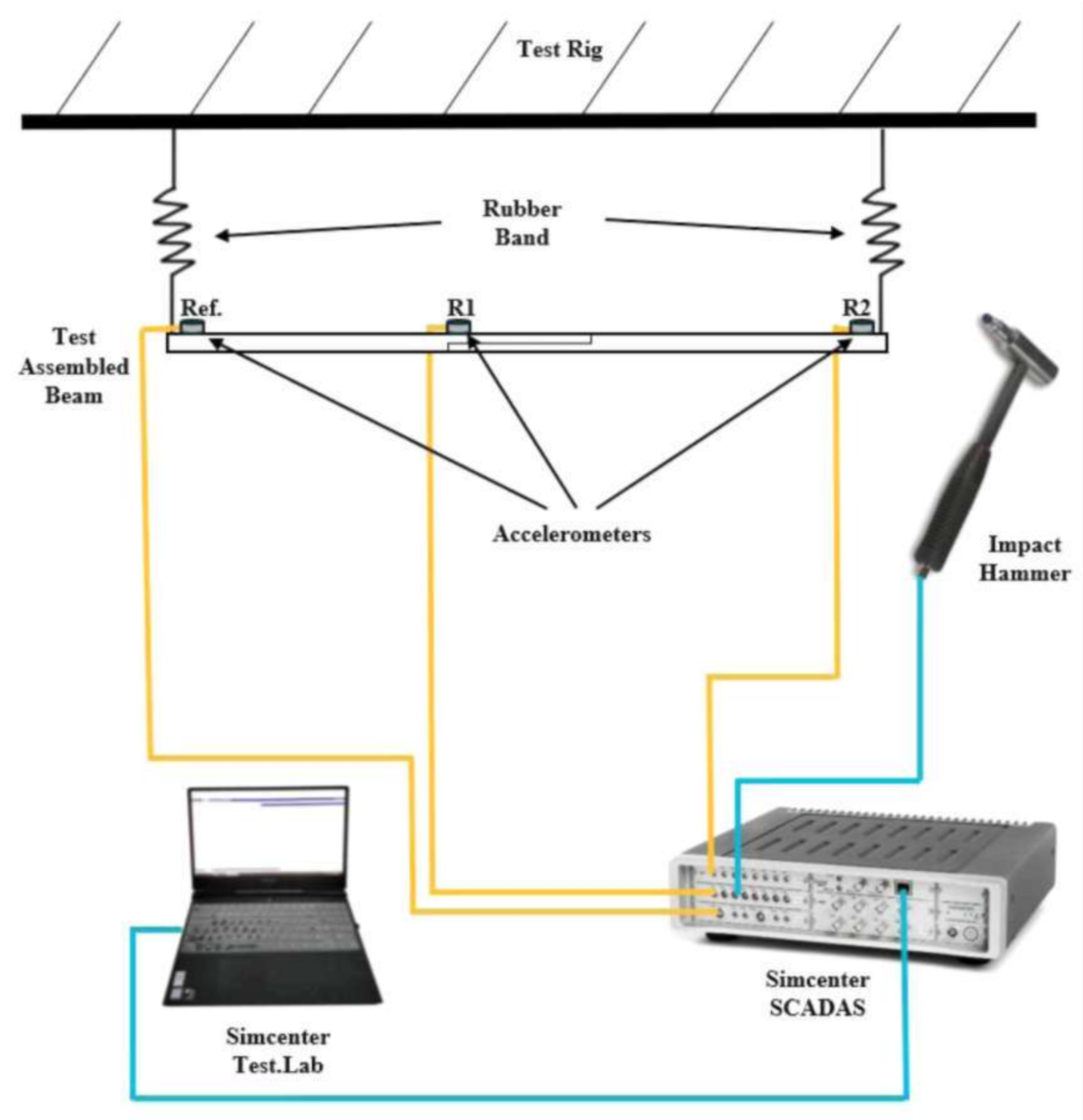


Figure 3.9 Schematic Diagram of EMA for Horizontal Direction

3.7.3 Horizontal 2 Corners

In the third setup, the structure was in a horizontal orientation; however, it was suspended with the use of only two corners instead of all four corners used in the previous setup (Figure 3.10). Two rubber bands with springs were used and one was attached at each end edge of the structure. This arrangement caused a small asymmetry in the suspension stiffness and support locations which was predicted to increase the variability of the boundary conditions and may potentially affect the measured modal response, especially at lower frequencies. This configuration was used to examine the robustness of the modal parameter identification for lesser uniform support conditions. To ensure consistency amongst all the tests, the effect of impact excitation and the accelerometer location was the same measurement procedure as the previous configurations.

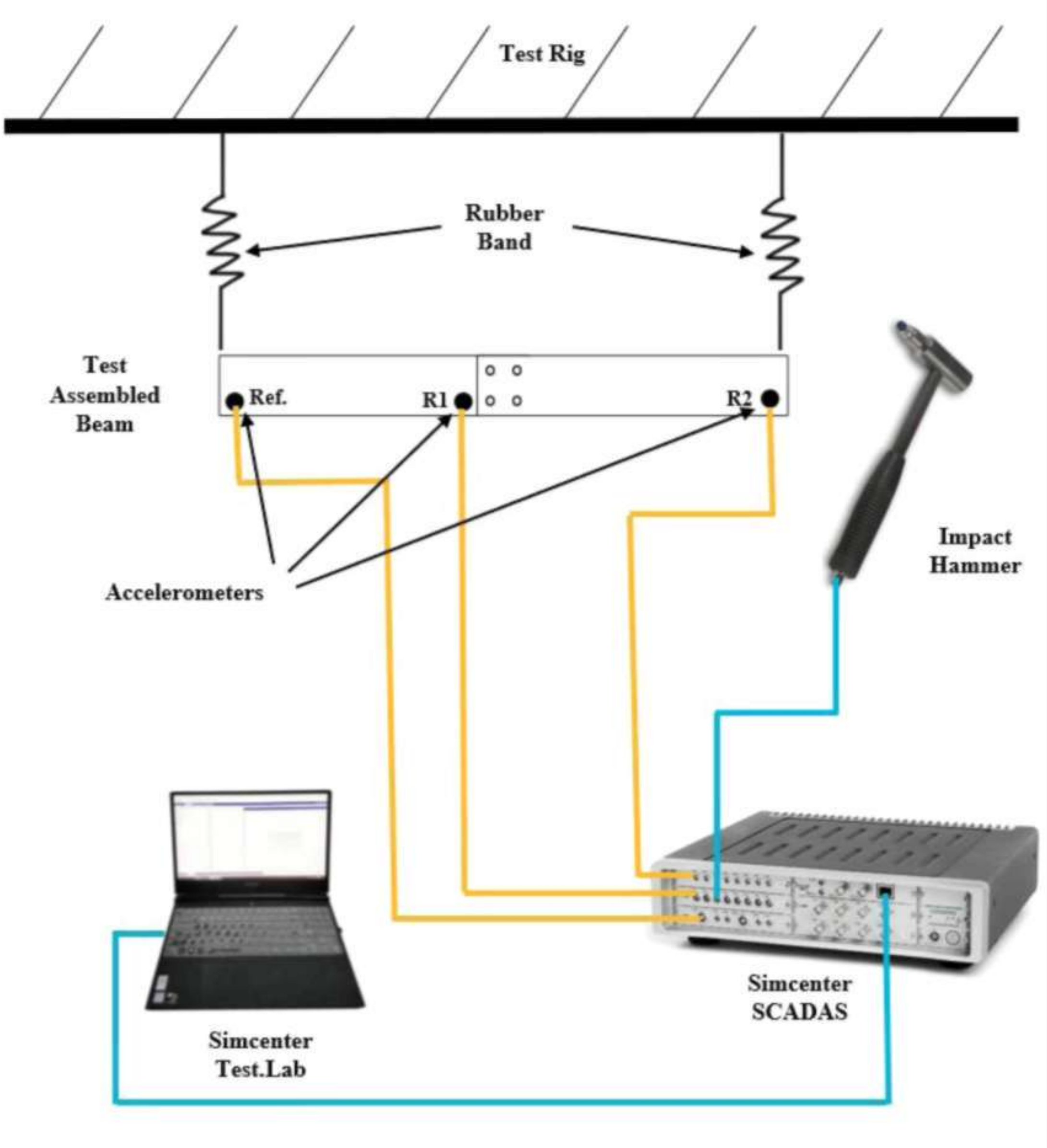


Figure 3.10 Schematic Diagram of EMA for Horizontal 2 Corners Direction

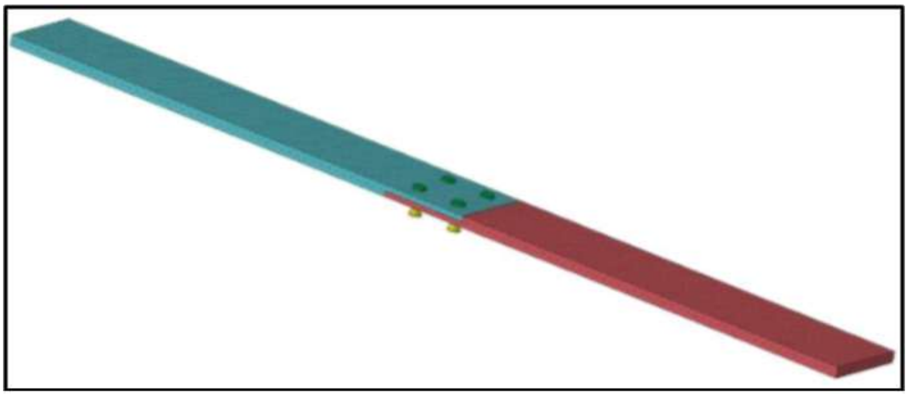
3.8 FE Modelling of the Substructures

The 3D CAD models of Substructure A and Substructure B were developed using CATIA V5 software and these models were used as the basis for the generation of their FE models. Both substructures were modelled based on the properties of Aluminium 7075 in accordance with the manufactured specimens used in the EMA tests. The information regarding the CAD representation of the test structure and the Hi-Lok fastened region is displayed in Figure 3.11.

FE discretisation for the substructures was conducted using solid elements with an element size of 5 mm, selected based on mesh (element size) convergence verification. Details of the mesh, including the number of nodes and elements are summarised in Table 3.1.

To make sure that the component FE models represent the test substructures properly before moving on to modelling the assembled structure, an FE model updating procedure was applied at the component level. The updating process was carried out in accordance with the methodology reported in [16-22, 29]. With the aim of reducing the difference between the modal parameters predicted by the FE and those obtained by EMA of the respective substructures.

Figure 3.11(b) is included to illustrate the physical configuration of the Hi-Lok fastener at the joint interface with the Hi-Lok pin (alloy steel) passing through the substructures and Hi-Lok collar (aluminium) seated on the outside surface to provide clamping. The material specifications typically adopted for modelling Hi-Lok fastener are summarised in Table 3.2, which lists the reference values (Young's modulus, Poisson's ratio and density) that are used in representing the Hi-Lok fastener in the FE-models.



(a)

(b)

Figure 3.11 (a) CAD Model of the Test Structure, (b) Hi-Lok Fastened Structure Close-Up

Table 3.2

Standard Values of Parameters of Hi-Lok

Description	**Value**	**Unit**
Modulus of Elasticity	190000	MPa
Poisson coefficient	0.3	Unitless
Density	7.85×10^{-6}	kg/mm^3

3.9 FE **Modelling of the Assembled Structure**

A total of four different FE models were created in order to examine the dynamic behaviour of the Hi-Lok fastened structure. The models were developed and analysed using MSC Patran as the pre-processing software and MSC Nastran as the solver. The four modelling techniques considered in this study include the solid Hi-Lok substructure model (Technique 1), the combined Hi-Lok substructure model (Technique 2), the simplified Hi-Lok substructure model (Technique 3) and an enhanced simplified Hi-Lok substructure model (Technique 4). Reference [115] is cited to acknowledge preliminary studies that motivated the choice of these four modelling strategies. However, all models used in this thesis were independently developed, analysed, and evaluated within the scope of the present work.

Following a range of mesh convergence tests, a combination of an element size of 5 mm with a tolerance of +-1 mm was selected, providing a trade-off between accuracy and computation efficiency. Convergence was assessed by monitoring the stabilisation of the first five natural frequencies as the element size was reduced. All the models were analysed using MSC Nastran Solution 103 (normal modes extraction) under free - free boundary conditions and the predicted natural frequencies and mode shapes were subsequently validated with the EMA results, which are presented in Chapter 4.

Technique 1, which is illustrated in Figure 3.12, represents the most detailed modelling technique. Both the substructures and the Hi-Lok fasteners were modelled using 3D 4-noded tetrahedral solid elements (CTETRA4), forming a full volume mesh. This technique yields a high-fidelity model of the joint region that can be used for comparison with the simplified models.

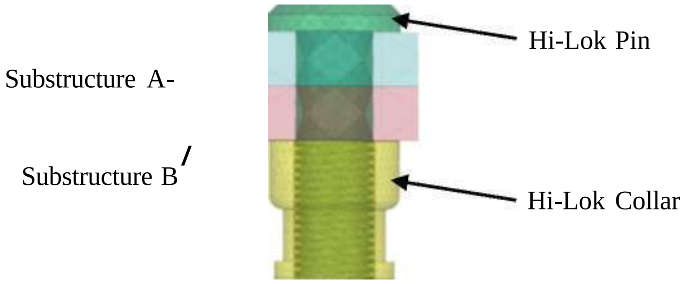
In Technique 2, which is presented in Figure 3.13, the substructures were again modelled using CTETRA4 elements in 3D and the fastener region was also represented using 3D solid elements. Compared to the other techniques, this approach retains a fully three-dimensional representation, but the modelling arrangement for the connection definition differs, leading to a larger model size and increased computational demand as reflected in Table 3.1.

Technique 3, shown in Figure 3.14 was developed in order to reduce the computational cost by modelling Substructures A and B using 2D 4-noded quadrilateral shell elements (CQUAD4). In this technique, the Hi-Lok pins and collars were simplified by 1D CBAR-element and the connection between the 1D fastener representation and shell substructures were represented by RBE2-element. This approach results in a significant reduction in the number of degrees of freedom while maintaining effective stiffness transfer between the substructures.

Technique 4, which is illustrated in Figure 3.15, is an enhanced version of the simplified modelling technique. In this technique, 3-noded triangular shell elements (CTRIA3) were introduced locally at the interface between Substructure A and Substructure B to improve mesh conformity around the fastener region and CQUAD4 elements were retained for the rest of the substructures. In addition to this, the 1D CBAR elements used in Technique 3 were replaced with RBE2 spider elements to represent the Hi-Lok fasteners between Substructures A and B. The RBE2 spider formulation distributes the connection constraints across multiple surrounding nodes, resulting in more realistic stiffness transfer within the joint region without increasing the mass, thereby improving the correlation with the EMA results at low computational demand.

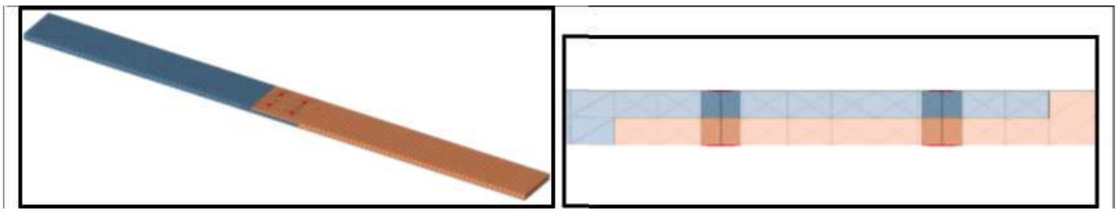
A summary of the element formulations, model sizes, and the corresponding nodes and elements for each technique is given in Table 3.1. This table facilitates comparison of the modelling fidelity and computational cost associated with the four techniques.

(a) (b)

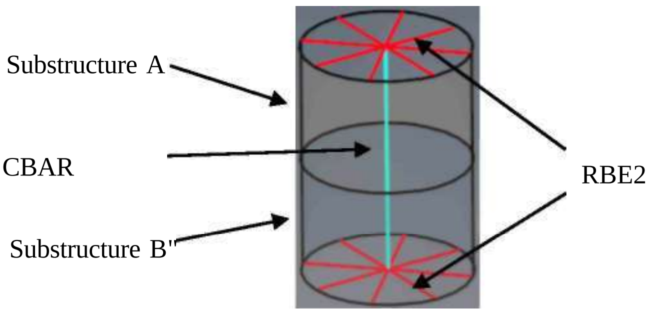


(C)

Figure 3.12 (a) FE Model of the Solid Substructures - Hi-Lok Model (Technique 1), (b) Meshing at the Hi-Lok Fasteners of Technique 1, (c) Close-Up View of the Hi-Lok Fasteners of Technique 1



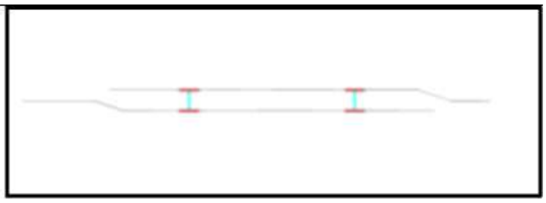
(a) (b)



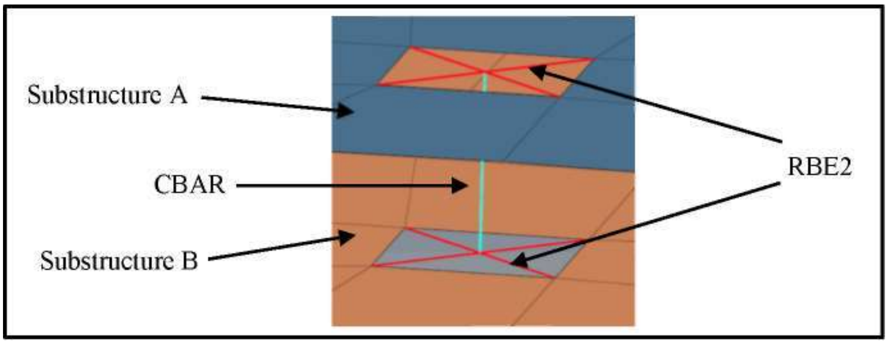
(C)

Figure 3.13 (a) FE Model of the Hybrid Substructures - Hi-Lok Model (Technique 2), (b) Cross Section at the Hi-Lok Fasteners of Technique 2, (c) Close-Up View of the Hi-Lok Fasteners of Technique 2

(a)



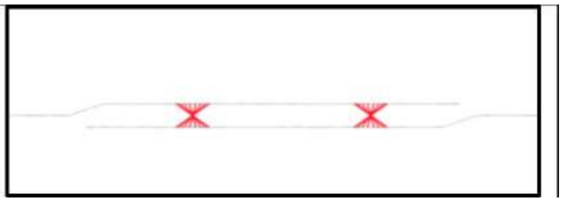
(b)



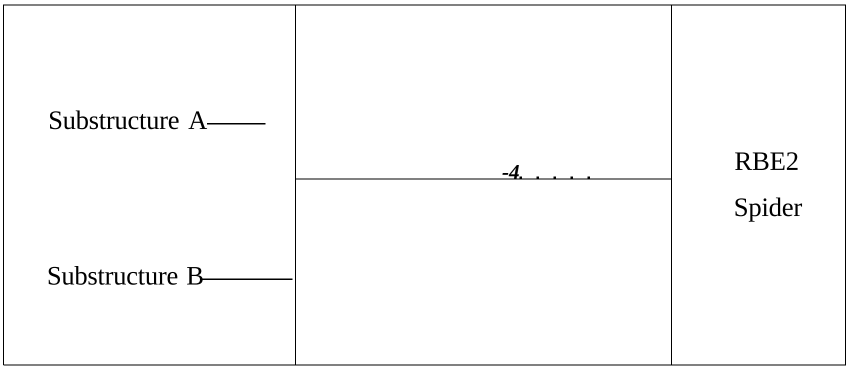
(c)

Figure 3.14 (a) FE Model of the Simplified Substructures - Hi-Lok Model (Technique 3), (b) Meshing at the Hi-Lok Fasteners of Technique 3, (c) Close-Up View of the Hi-Lok Fasteners of Technique 3

(a)



(b)



(c)

Figure 3.15 (a) FE Model of the Improved Simplified Substructures - Hi-Lok Model (Technique 4), (b) Meshing at the Hi-Lok Fasteners of Technique 4, (c) Close-Up View of the Hi-Lok Fasteners of Technique 4

3.10 Model Updating of the Substructures

The measured geometries of Substructure A and Substructure B were used together with the nominal material properties of Aluminium 7075 to develop the initial FE models of the individual components. Model updating was then carried out to increase the correlation between the values predicted by the FE and those experimentally measured through EMA. At this stage, only material properties, namely Young's modulus, mass density, and Poisson's ratio were selected as updating parameters.

No joint interfaces parameters were included in the updating process, as the substructures were tested without fasteners or contact interfaces. Consequently, the dynamic behaviour of each of the substructures was governed solely by its material properties and geometry. For this reason, MAC analysis was not utilized at this stage, as the goal of the updating of the substructures was to match the natural frequencies rather than to correlate assembled mode shapes.

The process of performing the update was to minimise the differences between the experimentally measured and FE-predicted natural frequencies by iterative changes in the selection of the material parameters within physically realistic limits. At each iteration, the new FE results were compared with the corresponding experimental frequencies and the parameter values were adjusted until satisfactory agreement was obtained.

Model updating was performed using FEMTools which uses a sensitivity-based updating approach to determine the optimal set of material properties that minimise frequency errors. Once good frequency correlation between the updated FE models and the EMA results of the substructures was achieved, these updated component models were subsequently used as the base line for constructing the FE model of the assembled structure.

3.11 Model Updating of the Assembled Structure

The assembled structure was constructed by linking the previously validated substructure FE models using simplified representations of the Hi-Lok fasteners. These connections were implemented using different element formulations such as CBAR, CBEAM, RBE2 elements as introduced in Section 3.9, to represent the transfer of mechanical stiffness across the joint while maintaining computationally efficient. The use of simplified connector elements allowed the predominant dynamic effect of Hi-Lok fasteners to be represented without the need to explicitly model contact and preload effects.

Similar to the substructure level updating, the model updating procedure for the assembled structure considered only variations in material properties, namely Young's modulus, mass density and Poisson's ratio. The values of the updating parameters were varied in the physically realistic limits, based on the value of material datasheets and acceptable engineering tolerances, to ensure that the updated model accurately represented the physical test structure.

To assess the level of agreement between the updated FE model and experimental results of the study, percentage error in natural frequencies and the MAC were used as correlation metrics. An acceptable frequency discrepancy of 5% or less was targeted, while a MAC value of 0.90 or higher was adopted as an indicator of good agreement between FE and EMA mode shapes.

EMA results obtained from the three suspension configurations, namely: horizontal, horizontal two corners, and vertical, were incorporated in the correlation and updating process. These different orientations were taken into account for variations in the boundary condition sensitivity and gravitational effects, particularly at the lower frequencies. Inclusion of results from different suspension configurations prevented the updated FE model from being turned to a single experimental setup, resulting in a more robust final model.

Material properties were iteratively adjusted until satisfactory agreement was reached between experimentally identified modal parameters and the approximations of the numeric method from the FE analysis in all test configurations. The final updated model showed acceptable correlation with the EMA results, providing confidence in the dynamic accuracy of the FE model of the assembled Hi-Lok fastened structure.

3.12 Concluding Remarks

This chapter has introduced the experimental and FE approaches used to investigate the dynamic behaviour of the Hi-Lok fastened structure. EMA was carried out on individual substructures as well as the assembled structure under three different suspension configurations, namely vertical, horizontal and horizontal two corner arrangements. These configurations were chosen to approximate free-free boundary conditions and to account for the effect of boundary sensitivity and gravitational influence, thereby providing a complete experimental basis for validating the FE models.

FE models of the substructures as well as the assembled structure were developed using the measured geometries and nominal material properties Updating of the FE models of the substructures was carried out by varying the selected material parameters to improve correlation with the experimentally measured natural frequencies. The validated substructure models were then assembled by means of four different Hi-Lok fastener modelling techniques, ranging from detailed three-dimensional modelling to simplified (connector-based) modelling. This enabled a systematic investigation of the trade-off between modelling accuracy and computational efficiency.

Validation of the FE models was carried out using the EMA results through frequency error metrics and MAC, with MAC evaluation applied specifically to assembled structure. The combination of several FE modelling techniques and diverse EMA suspension arrangements prevented model tunning to a single test condition, thereby enhancing the robustness of the validation process. The methodology developed in this chapter directly supports the research objectives and provide a reliable foundation for the results analysis and discussion provided in the next chapter.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the outcomes of both experimental and FE studies of the dynamic behaviour of the Hi-Lok fastened structure. This chapter focuses on the comparison of the modal parameters, namely natural frequencies and mode shapes, between measured and predicted results, for both the individual substructures and of the assembled structure.

The result of EMA of the individual substructures (Substructures A and B) and assembled structure under different suspension conditions are presented at the beginning of the chapter. These figures provide initial dynamic parameters and illustrate the effect of the jointed assembly on the overall response.

The corresponding FE investigation outcomes are then presented for both the substructure and the complete assembly. The reliability and accuracy of the FE models are accessed through comparison with the experimental results. To improve the correlation with experimental results, model updating was performed by tuning material properties using the FEM framework.

The last parts of this chapter point to the progress that was made after updating the models, where the correlation of the numerical and experimental outcomes is addressed. This evaluation models that can be further applied in the dynamic prediction and structural evaluation.

4.2 Correlation of EMA and FE Results for the Substructures

Table 4.1 shows the correlation between the experimentally measured natural frequencies by EMA and FE predicted results for Substructure A. The comparison is restricted to the first four modes, as these were the modes identified with a high level of coherence and repeatability within the selected frequency range during the test.

The individual frequency errors range between 0.27% and 3.96% with the largest deviation observed in the third mode. This deviation might be due to modelling idealisations and uncertainties in the representation of the local stiffness characteristics.

The total error of 7.63%, reported as the sum of the modal errors for each individual sub-structure, indicates that the FE model reproduces the dominant dynamic characters of sub-structure A with acceptable accuracy for further assembly level analysis.

The results of the correlation performed for Substructure B are summarised in Table 4.2. Consistent with Substructure A, the comparison is made with respect to the first four identified modes. The corresponding percentage errors lie between 0.13 and 2.19%, resulting in a total error of 5.15%. Slightly larger deviations observed in the second and fourth modes could be affected by experimental variability and modelling approximations. Overall, good agreement between the FE predictions and EMA measurements is observed for Substructure B, confirming the suitability of the model for subsequent assembled structure analysis.

The results for both substructures demonstrate the consistency with which the FE models reproduce the experimentally measured dynamic behaviour. These verified component-level FE models were thus used as the baseline for the modelling, correlation, and updating of the Hi-Lok fastened structure presented in the following sections.

Table 4.1
Comparison of Natural Frequencies Between the EMA and FE for Substructure A

		Substructure A	
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	413.90	414.99	0.27
2	986.55	1004.46	1.82
3	1320.97	1373.29	3.96
4	1724.20	1751.67	1.59
Total Error (%)			7.63
Number of Nodes		6458	
CPU Time (s)		4	
Memory Used (MB)		111	

Table 4.2
Comparison of Natural Frequencies Between the EMA and FE for Substructure B

	Substructure B		
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	413.75	414.29	0.13
2	985.00	1006.32	2.16
3	1321.72	1330.43	0.66
4	1720.10	1757.79	2.19
Total Error (%)			5.15
Number of Nodes		6803	
CPU Time (s)		4	
Memory Used (MB)		115	

4.3 Correlation of EMA and FE Results for the Assembled Structure

This section presents a comparative assessment of the assembled Hi-Lok fastened structure by EMA and four FE modelling techniques. The objective is to assess the accuracy and computational efficiency of each modelling approach in predicting the modal characteristics of the assembled structure. The EMA results are considered as the experimental reference, while the FE results are computed from the four modelling techniques described in Chapter 3. The comparison focuses on the first five experimentally identified modes, which consistently reproduced with acceptable coherence within the measured frequency range.

Table 4.3 presents the results of the correlation for Technique 1 in which both the substructures and the Hi-Lok fasteners are represented by completely three-dimensional solid elements. This approach results in very large discrepancies between FE and experimental natural frequencies, with a total error of 253.7% and an individual error of 80.4% in the first mode. The low correlation is attributed to excessive stiffness introduced by the fully solid fastener representation and the large number of degrees of freedom, which leads to a significant overprediction of the structural stiffness. Despite its very detailed geometric representation, the high computational cost and low level of prediction accuracy render this modelling approach unsuitable for efficient modal analysis of Hi-Lok fastened assemblies.

The results for Technique 2 are summarised in the Table in 4.4. In this technique, the substructures are modelled using three-dimensional solid elements whereas the Hi-Lok fasteners are modelled using one-dimensional connector elements. This hybrid modelling approach significantly reduces the model size and computational cost (CPU time reduces from 353 s to 10 s and the total frequency error reduces to 167.5%). Although the overall accuracy remains insufficient, the improvement relative to Technique 1 shows that simplifying the representation of the fastener reduces the stiffness of the artificial joints and improves correlation of the results with experimental data.

Table 4.5 presents the results of the correlation performed for Technique 3 in which the substructures are modelled with two-dimensional shell elements and the Hi-Lok fasteners modelled with one-dimensional connector elements. This modelling strategy yields a significant improvement in the accuracy, with a total frequency error of 4.6% with individual modal errors of less than 3.3%. The improved correlation is attributed to the more appropriate stiffness representation of the thin plate substructures using shell elements and the removal of redundant three-dimensional constraints at the joint interface. The huge reduction in the number of degrees of freedom also yields very low computational time, making this an example of physically informed simplification that enhances both accuracy and efficiency.

The best overall performance is achieved using Technique 4, as summarised in Table 4.6. This technique keeps shell elements for the substructures, while introducing a locally refined joint modelling strategy to improve the stiffness distribution between the connected components. The total frequency error is further reduced to 1.6%, with individual modal errors ranging between 0.1% and 0.7%. The model yields a low computational cost and the highest level of agreement with the experimental data. These results show that carefully designed refined representations of simplified fastener models can significantly improve predictive accuracy without increasing the demand of computation.

Based on the above results, it can be clearly concluded that modelling techniques using simplified one-dimensional and two-dimensional elements, as implemented in Techniques 3 and 4, provide superior correlation with EMA results compared with fully three-dimensional solid models. Technique 4 offers the best balance between accuracy and computational efficiency, making it a practical and reliable modelling technique for investigating the modal behaviour of assembled structures with multiple Hi-Lok fasteners.

Table 4.3
Comparison of Natural Frequencies Between EMA and FE Predictions for Technique 1

Technique 1			
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	86.430	155.901	80.4
2	303.346	429.882	41.7
3	533.100	831.532	56.0
4	610.247	863.792	41.5
5	762.325	1022.157	34.1
Total Error (%)			253.7
Number of Nodes		96091	
CPU Time (s)		353	
Memory Used (MB)		5696	

Table 4.4
Comparison of Natural Frequencies Between EMA and FE Predictions for Technique 2

Technique 2			
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	86.430	130.888	51.4
2	303.346	420.344	38.6
3	533.100	695.152	30.4
4	610.247	754.723	23.7
5	762.325	941.118	23.5
Total Error (%)			167.5
Number of Nodes		4990	
CPU Time (s)		10	
Memory Used (MB)		2800	

Table 4.5
Comparison of Natural Frequencies Between EMA and FE Predictions for Technique 3

Technique 3			
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	86.430	86.572	0.2
2	303.346	304.579	0.4
3	533.100	535.435	0.4
4	610.247	630.166	3.3
5	762.325	759.689	0.3
Total Error (%)			4.6
Number of Nodes		1361	
CPU Time (s)		3	
Memory Used (MB)		1500	

Table 4.6
Comparison of Natural Frequencies Between EMA and FE Predictions for Technique 4

Technique 4			
Mode	**EMA (Hz)**	**FE (Hz)**	**Error (%)**
1	86.430	86.349	0.1
2	303.346	304.705	0.4
3	533.100	536.824	0.7
4	610.247	608.283	0.3
5	762.325	761.710	0.1
Total Error (%)			1.6
Number of Nodes		14736	
CPU Time (s)		6	
Memory Used (MB)		896	

4.4 FE Mode Shape Comparison for the Substructures

This section covers a qualitative comparison of the mode shapes obtained from EMA and FE analysis for Substructures A and B. The primary objective of this section is to provide a visual evaluation of the mode shape similarity for the validated FE models before the analysis of the assembled structures, rather than reproducing the frequency correlation results already discussed in Section 4.2.

The FE models of Substructure A and B were prepared to represent undamped free vibration behaviour and were analysed using MSC Nastran Solution 103, based on nominal material properties and simplified boundary conditions. No model updating was performed at this stage. As shown in Tables 4.7 and 4.8, the visual comparison focuses on the first four modes, which were consistently identified in the EMA tests, exhibiting stable frequency estimates and clearly defined deformation patterns. These lower order modes dominate the dynamic response of the substructures in practical applications and are therefore the most relevant for validating the baseline FE representations.

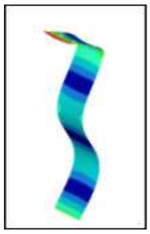
The comparison shows good visual agreement between the EMA and FE mode shapes for the first, second modes of both substructures, especially in the characteristics of global bending. Differences observed in the third and fourth modes are attributed to the increased sensitivity of higher-order modes to local stiffness variations, experimental noise and modelling idealisations, such as simplified boundary assumptions and uniform material properties. Such discrepancies are commonly encountered in component-level modal validation and do not undermine the overall suitability of the FE models.

Quantitative MAC values are not presented for the individual substructures, because the main goal of the component level validation was to achieve accurate frequency matching prior to assembly. Mode shape correlation using MAC is instead performed on the assembled structure level, where joint interaction and global deformation behaviour become significant, as discussed in the following section. The consistent visual agreement of the mode shapes observed in this section shows that the FE models of Substructures A and B provide an adequate basic for assembled-structure modelling and subsequent updating.

Table 4.7
Comparison of Mode Shapes Between EMA (left) and FE (right) Models for Substructure A

Mode	**EMA Mode Shape**	**FE Mode Shape**
1		
2		
3		
4		

Table 4.8
Comparison of Mode Shapes Between EMA (left) and FE (right) Models for Substructure B

Mode	EMA Mode Shape	FE Mode Shape
1		
2		
3	***mm***	
4		

4.5 FE Results and Model Refinement of the Assembled Structure

The results reported in the present Section are based directly on the validated component level FE models presented in Sections 4.2 and 4.4 and extend the study to the assembled Hi-Lok fastened structure. MAC values of the correlation results between EMA and FE predictions are presented in Table 4.9. These results show that Technique 4 provides the highest degree of mode shape correlation among the modelling approaches investigated. Modes 1 to 4 produce high MAC values (0.92, 0.98, 0.85 and 0.95, respectively), indicating strong agreement between experimental and numerical mode shapes. These findings confirm that the assembled-structure FE model, derived from the validated substructure models, successfully retain the dynamic characteristics of the component level.

Mode 5 shows a lower MAC value of 0.65, indicating reduced correlation compared with the lower modes. This mode was found to be a predominantly in-plane vibration mode, whereas the majority of EMA excitation was applied in the out-of-plane direction. As impact hammer testing is generally more effective at exciting out of plane bending responses, the limited excitation energy in the in-plane direction likely contributed to the reduced quality of the measured response for this mode. Consequently, the lower MAC value for the Mode 5 is attributed to limitations of the experimental excitation, rather than deficiencies in the FE model representation.

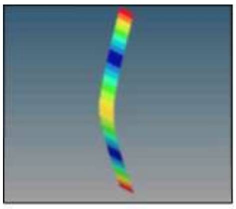
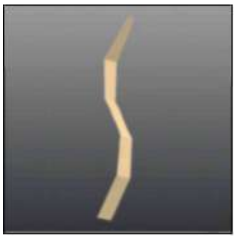
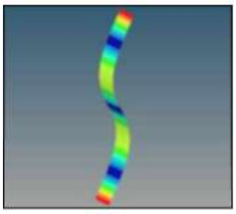
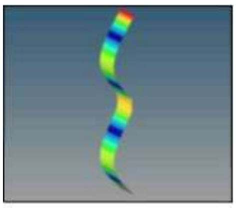
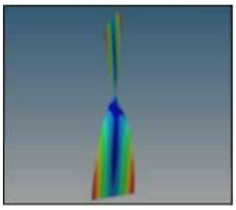
To further study the effect of mesh refinement on both the prediction accuracy and the computational efficiency for Technique 4, a mesh convergence study was performed. Two strategies of meshing were examined. The first strategy involved local mesh refinement around the Hi-Lok joint interface, while a coarser mesh was used elsewhere. The second strategy applied the same mesh size throughout the whole structure. These configurations are shown in Figures 4.1 and 4.2, and the corresponding convergence results are summarised in Table 4.10 and Figure 4.3. The frequency error values presented in the convergence study were computed as the percentage difference between the FE-predicted and EMA-measured natural frequencies, using the same formulation adopted earlier in third chapter.

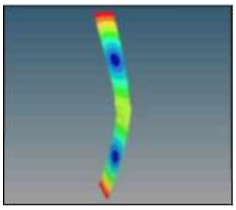
The results show that reducing the element size results in reduced frequency error, with a minimum error of 1.61 %, obtained for the 3mm + 1mm mesh configuration. However, this configuration is associated with a significant increase in computing cost, involving 31,718 elements, 16,269 nodes, and approximately 97,600 degrees of freedom. In this context, the degrees of freedom represent the total amount of independent displacement variables retained in the FE-model, which directly affect memory usage and solution time. Although this mesh configuration produces the most accurate numerical results, its computational demand renders it impractical for routine modal analysis.

By comparison, a 5 mm + 1 mm locally refined mesh configuration achieves a comparable level of accuracy of 1.64% with significant lower computational expense. This set-up provides an effective compromise between accuracy and efficiency by concentrating mesh refinement in areas of high stiffness gradients, such as. the fastener interface, while avoiding unnecessary refinement in less influence areas. The uniform mesh refinement strategy (shown in Table 4.11 and Figure 4.4) demonstrates a continuous reduction in frequency error with decreasing element size; nevertheless, this improvement is consistently followed by a large increment in the number of elements and degrees of freedom. This observation confirms that uniform mesh refinement is less efficient than selective local refinement for the present application.

Overall, these results justify the proposed selective mesh refinement strategy at the joint interface as a more efficient and practical technique for dynamic analysis of Hi-Lok fastened structures. Although the finest mesh configuration produces the lowest frequency error, the 5 mm plus 1 mm locally refined mesh configuration achieves the most balanced solution, in terms of accuracy and computational efficiency. Therefore, this meshing strategy was adopted as the optimal configuration for Technique 4, supporting its suitability as a reliable and computationally efficient FE modelling approach for predicting the modal behaviour of assembled structures with multiple fasteners.

Table 4.9
Comparison of Mode Shapes Between EMA (left) and FE (right) Models with MAC values

Mode	**EMA Mode Shape**	**FE Mode Shape**	**MAC**
1			0.92
2			0.98
3			0.85
4			0.95

5			0.65

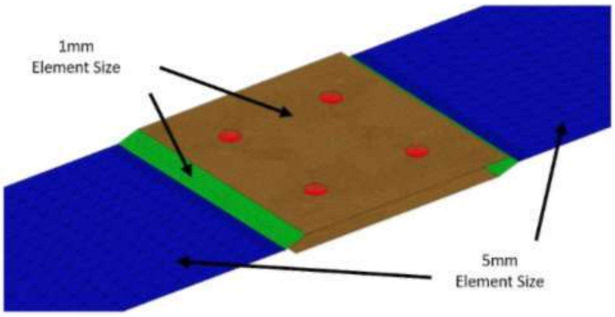


Figure 4.1 New Meshing Configuration on Technique 4

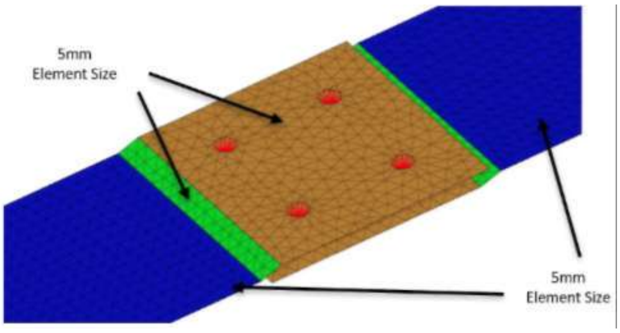


Figure 4.2 Initial Meshing Configuration for Technique 4

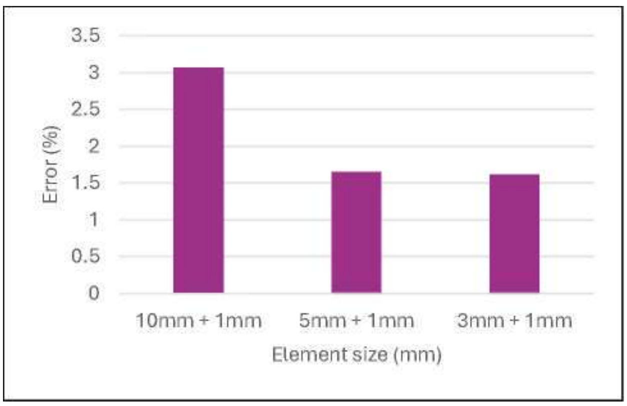


Figure 4.3 Convergence Test for New Technique 4

Table 4.10
Detailed Informations on New Technique 4

Element Size (mm)	Error (%)	Number of Elements	Number of Nodes	Number of DOFs
10mm + 1mm	3.066	27168	13870	83220
5mm + 1mm	1.643	28794	14736	88416
3mm + 1mm	1.61	31718	16269	97614

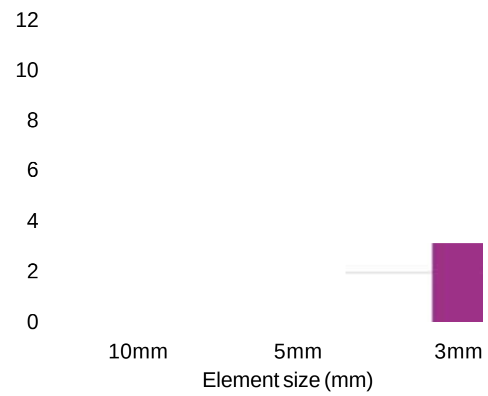


Figure 4.4 Convergence Test for Initial Technique 4

Table 4.11
Detailed Informations on Initial Technique 4

Element Size (mm)	Error (%)	Number of Elements	Number of Nodes	Number of DOFs
10mm	11.295	654	417	2502
5mm	5.061	2468	1402	8412
3mm	3.121	6772	3662	21972

4.6 Model Updating of the Substructures

Model updating of the substructures was performed after correlating the EMA and FE results presented in Section 4.2, with the aim of enhancing the level of agreement between the FE predictions and the experimental measurements. The updating process was performed separately on Substructure A and Substructure B before assembled structure modelling. The calculations were performed using FEMTools, which adopts a sensitivity-based updating approach.

In this study, only material properties, namely Young's modulus, mass density and Poisson's ratio, were selected as updating parameters. These parameters were selected because the predicted natural frequencies were sensitive to them, consistent with the approaches adopted in previous studies [18, 53]. The updating parameters were varied within physically reality limits; defined by material datasheet values for Aluminium 7075 and commonly used engineering tolerances. The mesh configuration, boundary conditions, and modelling assumptions, such as no damping, were kept constant during the updating process to ensure that the observed improvements of the correlation were only due to changes in material properties.

The standard and updated material properties, obtained by the model updating process for Substructure A and Substructure B are summarised in Table 4.12 and Table 4.13, respectively. All the material properties are presented in consistent SI units. The updated values yield only small deviations from the nominal properties, indicating that minor parameter adjustments were sufficient to improve frequency correlation.

The updating process effectiveness is evidenced by the reduction in frequency discrepancies between the FE predictions and the experimental results. Improved agreement is observed for all identified modes when compared with the pre-updated models, as discussed in Section 4.2. At this stage, MAC analysis was not performed, because substructure-level updating focused exclusively on matching natural frequencies, rather than matching mode shapes. By contrast, mode shape correlation using MAC was conducted at the assembled-structure level, where joint interaction and global deformation behaviour is more important.

The updated material properties obtained from the substructure-level updating were subsequently adopted as the final parameter values for modelling the FE model of the Hi-Lok fastened structure. This ensured that the assembled-structure analysis was based on substructure models that were already calibrated against experimental data, thereby providing a consistent and reliable base for the assembled-structure updating and validation presented in the following sections.

Table 4.12
Parameters Used in Substructure A

Description	Standard Value	Updated Value	Unit
Modulus of Elasticity	70,200	69,895.02	MPa
Poisson coefficient	0.3	0.384811	Unitless
Density	2.72×10^{-6}	2.71×10^{-6}	kg/mm^3

Table 4.13
Parameters Used in Substructure B

Description	Standard Value	Updated Value	Unit
Modulus of Elasticity	70,200	69,902.26	MPa
Poisson coefficient	0.3	0.379136	Unitless
Density	2.72 X 10^{-6}	2.71 X 10^{-6}	kg/mm^3

4.7 Model Updating of the Assembled Structure

Following the substructure-level updating presented in Section 4.6, the model updating was performed on the assembled Hi-Lok fastened structure to further improve the agreement between the FE predictions and the EMA. The assembled FE model was built using the updated substructure models and Hi-Lok fasteners as simplified connector elements, namely CBAR, CBEAM, RBE2, as described in Chapter 3. The process of updating was conducted using FEMTools, which uses a sensitivity-based updating method.

In the assembled structure updating, only the material properties were adjusted only, consistent with the substructure- level updating strategy. Young's modulus, mass density, and Poisson's ratio were varied within physically realistic bounds, defined by Aluminium 7075 material datasheet values and acceptable engineering tolerances. The mesh configuration, connector definitions, and boundary condition assumptions were fixed. This ensured that any improvement in correlation was solely due to changes in material properties, rather than to modifications in modelling topology, contact modelling and interface stiffness assumptions, which were outside the scope of this study.

The updated assembled model was validated by using the frequency error metrics and also MAC in order to quantify the similarity between the EMA and FE mode shapes. As it can be seen from table 4.9, the post-updated model achieved MAC values in the range of 0.65 - 0.98, indicating generally good mode shape correlation for the dominant modes. The lower MAC value corresponds to the fifth mode, which is predominantly an in-plane mode and was more difficult to excite and measure reliably using the impact testing configuration. In addition to the improvement in the mode shape correlation, the updated assembled model achieved a dramatic reduction in frequency differences compared to the pre-updated model. This improvement is characterised by the reduction of large initial errors, observed in the least suitable modelling approaches, to low residual errors in the updated assembled model, thereby confirming a substantial enhancement in predictive accuracy after updating the assembled model.

Overall, the results confirm that substructure-level updating provides robust foundation for assembled-structure modelling, and the assembled-structure updating further enhances agreement in both frequencies and mode shapes. The final updated assembled model therefore constitutes a consistent and computationally efficient model of the dynamic behaviour of the Hi-Lok fastened structure used in subsequent analysis.

4.8 Concluding Remarks

This chapter has presented the experimental and numerical evaluation of the dynamic behaviour of the Hi-Lok fastened structure for both substructure and assembly levels. EMA provided the reference modal parameters for Substructures A and B, and for the assembled configuration under the selected suspension arrangements, enabling systematic correlation with the FE predictions. The substructure-level results confirmed that the baseline FE models reproduced the predominant dynamic behaviour of the substructures with acceptable frequency agreement, thereby providing a reliable foundation for subsequent assembled-structure modelling.

The assembled structure comparisons showed that the modelling strategy plays a decisive role in determining both prediction accuracy and computational cost. Fully three-dimensional solid modelling of the fasteners introduced excessive stiffness and failed to yield good h correlation with the EMA and resulted in high computational demand. In contrast, simplified representations based on one-dimensional and two-dimensional elements achieved substantially improved agreement. Technique 4 was found to provide the most favourable balance, yielding the lowest overall frequency error, and strong mode shape correlation for the dominant modes, as indicated by the reported MAC values. The lower MAC value obtained for the fifth mode pointed out sensitivity of in-plane modes to the excitation direction and measurement quality, rather than indicating a fundamental limitation of the modelling approach.

Sensitivity-based model updating using FEMTools further improved the agreement between the FE and EMA results. The updating strategy focused on physically realistic changes in the material properties, while maintaining the modelling topology and boundary assumptions, thereby, increasing confidence that the observed improvements resulted from updated stiffness and mass properties rather than numerical tunning without physical justification. The mesh convergence study demonstrated that selective local refinement around the joint interface is more efficient than uniform mesh refinement. The adopted meshing strategy resulted in near optimum accuracy without incurring unnecessary computational cost, thereby supporting the use of simplified models for practical modal prediction of fastened structures.

Overall, the results of this chapter confirm the feasibility of accurately and efficiently modelling the dynamic behaviour of Hi-Lok fastened structures using physically informed simplification of the fastener representations, the targeted mesh refinement, and systematic experimental validation. The validated and updated models developed herein establish a strong foundation for and support the broader objective of developing computationally efficient modelling methodologies for aerospace-type fastened structures.

CHAPTER 5
CONCLUSION AND FUTURE WORK

5.1 Conclusions

The aim of this work was to study the dynamic behaviour of a Hi-Lok fastened structure by a combined experimental and numerical approach through the aim of developing an accurate and computationally efficient FE modelling technique for such assemblies. EMA was performed in order to derive reliable information regarding the natural frequencies and as well as the mode shapes and these measurement data were used to test and validate the proposed modelling approach.

A one dimensional, element-based FE modelling technique was developed and used for an accurate modelling of the natural frequencies and mode shapes of the physical Hi-Lok fastened structure. In the current approach, the Hi-Lok fasteners were modelled by using one-dimensional elements whereas the substructures were modelled by appropriate structural elements. The results demonstrate that the necessary dynamic behaviour of the fastener and joint region can be reproduced using a physically motivated simplification of the fastener and joint region without having the high stiffness and high computational costs often related to fully three-dimensional solid modeller to model fasteners and surrounding substructures.

The natural frequencies and the mode shapes of Hi-Lok fastened structure were then determined using the proposed modelling technique as well as EMA. EMA was able to provide uniform modal parameters for the assembled configuration that were used to provide a robust experimental baseline. Using the proposed FE strategy, the predicted modal characteristics exhibited good agreement with the experimental ones and interpret the dominating dynamic features of structure, while the mode shape comparisons signify good correlation over the frequency range of interest.

The prediction capability for efficiency and accuracy of the proposed modelling technique was assessed by comparing the natural frequencies and the mode shapes, directly predicted and EMA associated ones. Systematic FE-EMA correlation showed the good balance between restoring the predictive accuracy and the efficient computation for the simplified fastener representation. Compared with the solid-fastener approaches with a high level of detail, the proposed technique reduced the computational cost and agreed well in terms of frequency prediction and mode shape correlation.

Overall, results of this study show that it is possible to accurately predict the dynamic behaviour of Hi-Lok fastened assemblies by an accurate and simplified physically informed FE modelling strategy validated with EMA data. The results confirm that the proposed one-dimensional fastener representation gives a practical and scalable way of analysing large, fastened aerospace structures where the predictive capability as well as the computational demand are critical.

5.2 Future Work

Although this study has been valuable in developing and validation of effective FE models in studying the dynamic behaviour of Hi-Lok fastened structures, there are still some areas in which further research and enhancement can be carried out:

1. Incorporation of Joint Interface Modelling:

Future research can be done to incorporate the joint interface characteristics like the contact stiffness and friction so as to represent the complex nature of fastened assembly when subjected to dynamic loads. This would increase the model capabilities to be applied to a more realistic aerospace joint condition.

2. Extension to Higher Modes and Broader Frequency Ranges:

The analysis was performed to pay attention to the initial several natural frequencies and the mode shapes. The wider frequency bands and the higher-order modes in the analysis would give a comprehensive dynamic characterization particularly in the case of wide-spectrum excited structures.

3. Experimental Testing with Alternate Excitation Techniques:

The findings were that the in-plane modes showed low MAC accuracy. Such modes can be better seen and correlated with alternative excitation techniques offerings, including shaker testing, or multi-directional hammer impacts.

4. Nonlinear Dynamic Behaviour and Damping Effects:

In this work linear elastic behaviour of material and undamped responses are assumed. Future model could include damping models and possible non-linearities in the form of joint slip, preload loss or bolt relaxation.

5. Application to Full-Scale Aerospace Structures:

The model that has been proved to work may be applicable to more complicated and higher-sized aerospace assemblies where there are numerous Hi-Lok fasteners. It would enable them to evaluate scalability, resilience and feasible application in engineering practice.

6. Fatigue and Stress Analysis Integration:

By application, the finer mesh structures evolved in this research can be exploited to determine the fatigue life of various structures and calculations of stress concentration particularly in some areas close to the fastener interfaces.

Tackling these elements will help to improve the dynamic modelling of fastened structures even more in future and will help towards more accurate design, durability analysis and optimization with respect to aerospace and other mechanical engineering applications.

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APPENDICES

APPENDIX 1


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AUTHOR'S PROFILE

Muhammad Syafiq Aiman Mohd Kahar holds a Diploma in Mechanical Engineering from Universiti Teknologi MARA (UiTM) Pasir Gudang, and a Bachelor of Mechanical Engineering (Hons.) from UiTM Permatang Pauh. He is currently pursuing his Master's Degree in Mechanical Engineering at UiTM Shah Alam. His research interests include structural dynamics, EMA, and FE modelling, particularly in the context of aerospace structures and fastened assemblies. His postgraduate research focuses on the dynamic characterization and model updating of Hi-Lok fastened structures using advanced simulation and testing tools such as Simcenter Testlab, MSC Nastran, Altair HyperMesh, and FEMtools. Syafiq is actively involved in academic research and aspires to contribute to high-impact studies in the field of structural engineering and aerospace mechanics.

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[5] Predicting Vibration Characteristics of a Bolted Pipe Assembly with Complex Boundary and Interface conditions via the Frequency Based Sub structuring Method (Accepted and waiting for publication in September 2025, JMechE).

[6] Efficient Modelling Methodology for Accurate Prediction of the Modal Characteristics of a Hi-Lok Structure (Under corrections, Asean Engineering Journal).