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OPTIMIZING THE PRODUCTION OF LAYERED SYSTEMS INCORPORATING MFC TRANSDUCERS AND MODELING BOLT JOINT LOOSENING DETECTION WITH THEIR APPLICATION

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Abstract: This article offers a concise overview of cutting-edge techniques for monitoring bolt joint looseness and optimizing Macro Fiber Composite (MFC) based structure manufacturing for structural health monitoring emphasizing MFC-host structure attachment methods, optimal MFC placement, and the impact of adhesive layers between MFC and the host structure. The study also employs Ansys software to conduct Multiphysics modelling and characterization of bolt joint conditions using MFC piezoelectric transducers. Emphasizing joint looseness under varying pretension loads, the results demonstrate that increasing preload, up to the full tightening torque value (14.5 Nm), increases the natural frequency, indicating enhanced joint stiffness. Conversely, looser connections result in lower natural frequencies, signifying decreased joint stiffness. The article focuses on assessing the effectiveness of Macro-Fiber Composite (MFC) for monitoring the health of bolt joints, providing a simple and efficient method for modelling the structural response of MFC-integrated bolt joints, facilitating convenient and rapid engineering analysis and testing.

Key words: Piezoelectric transducer, Macro Fiber Composite (MFC), Bolt joint looseness, Intelligent fault detection, Structural Health Monitoring (SHM), Multiphysics Modelling.

1. INTRODUCTION

Engineering structures and systems are designed with specified environmental limits, and material choices are made based on properties. Prototypes and experimental testing are common, but approximations and assumptions exist in both experimental and numerical approaches. A true understanding of a structure's behaviour only emerges during in-service use. Overdesign principle with conservative factors of safety is a common solution, resulting in heavy and costly structures. In weight-critical situations, marginal factors of safety may lead to failures or damage. Routine inspections are used for damage repair but incur additional costs. To address these limitations, intelligent fault and/or damage detection systems have been introduced. These systems enable operations close to the safety margin, reducing the need for frequent inspections and lowering material costs [1]. Regulatory bodies currently restrict 'safety-critical' systems with no margins, but addressing non-critical failures through monitoring could accelerate the acceptance of intelligent fault and/or damage detection systems. Intelligent fault detection systems are relevant to all the engineering disciplines. One of the disciplines where intelligent fault detection systems concerned is mechanical structures. According to the source [2] approximately 70% of mechanical failures are attributed to fastener issues. Mechanical fasteners, particularly bolt joints, are indispensable in engineering structures like aerospace, machinery, and civil infrastructure due to their ease of assembly and disassembly and their ability to bear heavy loads [3]. However, these bolted joints are prone to various failure modes, with self-loosening being a significant concern arising from inadequate preload, fluctuating loads, or harsh environments [2, 3]. Self-loosening poses a considerable risk, especially in inaccessible or critical locations, necessitating the monitoring of bolt preload to ensure structural safety and reliability. By implementing advanced intelligent monitoring systems, it is possible proactively address potential issues, thereby safeguarding the integrity and operational continuity of essential engineering systems.

The traditional method of inspecting joints connections by humans has the problems of being labour-intensive, the inspector often exposed to unsafe conditions and an uncomfortable working environment, and the inspection must be performed when the structure is not in use [4]. These problems definitely need to be addressed by involving intelligent damage detection systems that could monitor the status of the joint in real-time bases. These systems can be regarded as Structural Health Monitoring (SHM).

Over the past two decades, numerous researchers have pioneered real-time Structural Health Monitoring (SHM) techniques. These methods typically involve collecting and analysing data from onboard sensors to continuously assess the condition and structural integrity of bolt joints during operation and over their lifespan. One of the most common techniques of monitoring of bolt loosening is impedance-based techniques [3]. According to [5], the impedance-based technique involves applying high-frequency vibrations to a structure using surface-bonded piezoelectric transducers. The impedance of the structure is then measured by monitoring the current and voltage applied to these transducers. Changes in impedance signal structural changes, indicating possible damage. Piezoceramics are commonly used for this technique due to their high structural stiffness and ability to interact with dynamic systems across a wide frequency range [6].

However, piezoceramics have practical limitations, such as being brittle and prone to breakage, as well as difficulty conforming to curved surfaces. Moreover, there is a significant mass penalty associated with the use of lead-based piezoceramic materials. To address these issues, this paper proposes the use of Macro Fiber Composite (MFC), developed by NASA, as an optimal piezoelectric transducer for impedance-based health monitoring of bolt joints. MFC is a composite actuator that combines an active piezoceramic fiber phase with a polymeric matrix, overcoming the limitations of traditional piezoceramics and offering an effective solution for monitoring the health of bolt joints [7].

The Gliwice centre – Faculty of Mechanical Engineering, Silesian University of Technology - has been conducting research for years on the modelling, application and testing of piezoelectric transducers used in systems for damping mechanical vibrations, their excitation, as well as applications in systems for recovering electrical energy from mechanical vibrations. Particular attention is paid to the use of non-classical composite piezoelectric transducers due to their properties increasing the effectiveness of the designed systems and the number of potential possibilities of their application in modern technical means. Previous work has been published in numerous scientific studies [8-12]. This study is a continuation of these works and a research report on the possibility of using non-classical MFC piezoelectric transducers in systems for testing and monitoring the technical condition of selected structural elements.

This article offers a concise overview of advanced fault detection techniques and optimal manufacturing processes for MFC-based smart structures, tailored for applications like structural health monitoring and energy harvesting. The review systematically investigates the three key aspects crucial for optimizing the manufacturing process of MFC-based smart structures. Firstly, it explores various attachment methods for integrating MFCs with host structures. Secondly, it examines the optimal placement of MFCs on these structures for enhanced performance. Lastly, the article investigates the impact of adhesives on the overall effectiveness of the smart structure. By focusing on these aspects, the review aims to contribute valuable insights into refining the manufacturing processes and improving the functionality of MFC-based smart structures in real-world applications.

Additionally, in this article, a crucial examination is conducted through Multiphysics modelling to assess the looseness of bolt joints. The assessment is based on the impedance-based technique, employing MFCs as piezoelectric transducers. The modelling process utilizes the ANSYS software tool, revealing a straightforward and effective approach to understand the structural response of bolt joints integrated with MFCs. This method streamlines the engineering analysis and testing procedures, offering a convenient and rapid means to evaluate the integrity and performance of such joints with minimal cost. The use of MFCs as transducers adds a novel dimension to the intelligent fault detection systems assessment, showcasing the versatility and applicability of impedance-based techniques in SHM.

2. INTELLIGENT FAULT DETECTION METHODS

Intelligent fault detection systems span various engineering disciplines and are categorized as Structural Health Monitoring (SHM), Non-Destructive Evaluation (NDE), Condition Monitoring (CM), and Statistical Process Control (SPC) [1]. SHM involves online monitoring of structures like aircraft and buildings using sensors like optical fibers and strain gauges. CM focuses on rotating machinery, using online vibration-based techniques with accelerometers. NDE typically occurs offline, characterizing and checking damage severity using techniques like ultrasound and thermography. SPC is process-based, monitoring changes in processes with various sensors. Despite diverse applications, these areas share similarities and require a unified approach for intelligent fault detection beyond simple threshold methods. Techniques for processing sensor signals and deriving quantifiable features are essential for advancing damage evaluation and they are going to be the focus of next research work.

For the rest of this article, structural health monitoring (SHM) denotes an integrated method for intelligent fault detection in mechanical structures, with a specific emphasis on mechanical bolted joints. Structural Health Monitoring (SHM) is a vital process for assessing the condition and performance of mechanical engineering infrastructure. As described in detail by [13], SHM involves continuous observation of a structure or mechanical system through regularly spaced measurements. These measurements enable the extraction of damage-sensitive features, which are then subjected to statistical analysis to ascertain the current state of the system's health. In the long term, SHM provides updated information on the structure's ability to function as intended, considering the inevitable effects of aging and damage accumulation in operational environments. During sever conditions or defects in structures to be monitored, Structural Health Monitoring (SHM) acts as a swift assessment tool, providing timely evaluations of system functionality and structural soundness. SHM involves gathering and analysing data from onboard sensors to assess structural health [3].

This paper delves into the classical approaches to structural health monitoring (SHM) utilizing bonded sensors to the structure. However, it is crucial to acknowledge and briefly introduce the recent progress in bolt looseness detection enabled by diverse artificial intelligence techniques (digital technologies). This brief mention serves as an initial exploration for our future research in the integration of digital technologies for improved bolt looseness detection. Thus, some of the prominent works in this filed is presented as follows. A study by [14] compares single and meta-classification strategies for fault diagnosis in actuator systems within the DISESOR project. Utilizing both hard and soft computing methods, the authors propose a novel approach to parameter tuning for classifier optimization. Results suggest that simple classification schemes adequate for industrial actuators, with automatic parameter tuning enhancing accuracy and sensitivity, offering effective and less complex fault detection and isolation systems applicable for online and offline diagnosis. Another research work by [15] introduces a model-free fault detection and isolation method aiming to optimize diagnostic schemes automatically for maximal efficiency. By combining discrete wavelet analysis, machine learning (decision trees or artificial neural networks), and evolutionary algorithms, it addresses fault detection in systems like wind turbines. A work by [16] proposes a non-destructive method for assessing bolted joint health using percussion-based techniques and machine learning. By analysing the unique sounds produced during tapping and employing power spectrum density and a decision tree model, the method demonstrates high accuracy in detecting bolt looseness. A recent study by [17] presents an efficient structural damage detection system utilizing 1D Convolutional Neural Networks (CNNs). This system integrates feature extraction and classification seamlessly, employing an adaptive design for rapid and precise detection. By analysing real-time vibration data, it automatically identifies optimal damage-sensitive features from raw acceleration signals. The method exhibits outstanding performance and computational efficiency, as demonstrated through extensive experiments conducted on a grandstand simulator at scale. A study by [18] also introduces a fault diagnosis model, TSCNN, aimed at improving the accuracy of bolt-loosening diagnoses by simultaneously extracting fault features from vibration signals and time-frequency images. Through practical experiments on a machine tool guideway, the proposed model demonstrates an impressive average recognition accuracy of 99.58% for end-to-end bolt-loosening fault diagnoses, showcasing effectiveness and robust noise immunity.

Several methods utilizing contact sensors for Structural Health Monitoring (SHM) have been documented, particularly focusing on the detection of bolt loosening across various structural systems. These approaches encompass vibration-based, impedance-based, and guided wave-based techniques [19].

In vibration-based methodologies, the emphasis lies on leveraging global dynamic properties, including resonant frequencies, modal shapes, and frequency response functions, to identify bolt loosening [20]. A research by [21] investigates the impact of preload on the natural frequency of bolted structures under low-velocity impacts. Through experimental and simulated analyses, it has been observed that increasing preload initially increases the natural frequency of the structure until reaching a peak, then decreases until matching the initial tension, and finally rises again. I have also been revealed that the reduction in natural frequency the joint correlates linearly with decreasing the preload in the joint.

Nevertheless, the challenge arises from the fact that assembled structures typically consist of numerous bolts and joint interfaces, constituting local structural elements. Consequently, alterations in bolt preload at a localized position may not significantly affect global structural dynamic properties [22]. As a result, vibration-based SHM techniques exhibit relatively low sensitivity towards changes in bolt preloads, thus compromising their monitoring capability. The other candidate is guided wave based SHM techniques. Guided wave-based schemes offer advantages such as cost-effective, easily integrated transducers, capable of large area scanning with fewer transducers, high-frequency excitation for detecting minute damages, immunity to low-frequency ambient vibrations, and less impact from structural damping [23]. However, challenges arise from the complexities of guided wave propagation and interaction with damage, including multi-modal waves, dispersion, reflection clutter, and influences from environmental factors, instrumentation, ambient noises, and operational conditions [22].

Over the past two decades, impedance-based techniques have undergone significant development. Impedance-based techniques are characterized by monitoring mechanical impedance variations due to damage or defects in the structure. The variation of mechanical impedance is linked with the electrical impedance of piezoelectric transducers (PZTs) attached to the structure detect damage [24]. Previous research has demonstrated the effectiveness of these methods in identifying bolt loosening [5, 25], wherein a PZT attached to a bolt-jointed structure detects changes in electrical impedance to determine bolt preload [26]. However, practical implementation faces challenges due to the brittle nature of PTZ ceramics and their limited adaptability to curved surfaces. This study proposes the utilization of Macro Fiber Composites (MFC) for real-time monitoring of bolt joint health. The flexible nature of MFC allows the material conforming to a curved surface easily. Additionally, an MFC patch even has larger actuation forces than a PZT patch, since the $\boldsymbol{d_{33}}$ effect dominates the actuation mode in MFCs.

The study utilizes commercial ANSYS software for modelling and characterization. The choice of MFC showcases their promise as piezoelectric transducers for health monitoring. The research investigates the relationship between bolt pretension values and signal outputs, with a specific focus on changes in natural frequency and voltage generation.

3. A BRIEF REVIEW ON OPTIMIZING MFC-BASED SMART STRUCTURE MANUFACTURING

The increasing demand for miniaturized, autonomous, and effective active health monitoring systems, alongside smart energy harvesting, highlights the necessity for advanced design approaches, such as structural optimization and optimal control. In the realm of structural health monitoring, which involves integrating sensors and actuators via control systems, these structures can detect environmental shifts, diagnose specific problems, and analyse data to implement corrective measures. This capability enhances system efficiency and ensures structural integrity and safety. The development of methods for designing smart structures is a promising research area driven by the increasing demand and diverse applications. Piezoelectric ceramics, such as PZT, are commonly used to generate mechanical force or serve as sensors in control systems. The deformation of piezoelectric materials produces an electric charge, and conversely, they undergo mechanical deformation when exposed to an electric field. In the past decade, composite piezoelectric devices like the MFC have been developed as an alternative to monolithic homogeneous ceramic inserts. The MFC consists of a planar array of PZT rods with comb-shaped electrodes embedded in polymeric layers. By distributing PZT in thin rods, a flexible structure is created, allowing it to be bonded to curved structures, addressing the brittleness of PZT ceramic material.

A study by [27] presents a self-powered structural health monitoring (SHM) system utilizing macro-fiber composite (MFC) patches, integrating actuation, sensing, and energy harvesting functions. MFC patches serve as energy harvesters during normal vibrations, sensors for abnormal loadings, and actuators during maintenance, all while monitoring structural response. Experimental validation on a cantilevered composite laminate prototype with six MFC patches supports system feasibility, including recharging a 3V-65mAh Li-ion battery. The study further assesses a condition-monitoring algorithm's effectiveness in detecting faults and minimizing false alarms through simulations during maintenance.

Part of this research article conducts a thorough review of advanced optimization methods for MFC-based smart structures employed in structural health monitoring. The primary emphasis lies in examining optimization strategies related to MFC-bonded techniques, the optimal placement of MFC on the host structure, and the optimization of adhesive thickness. The study aims to provide a comprehensive overview of the current state of these optimization approaches, making easier to understand on their applications and effectiveness in enhancing the performance of MFC-based smart structures for structural health monitoring purposes.

The study conducted by [28] investigated the impact of the MFC-bonded technique on the performance of macro-fiber composite (MFC) in micro-energy harvesting and structural health monitoring. Two MFC-bonding techniques were explored: embedding the MFC patch inside the turbine blade and bonding it onto the surface. EpoxAmite 100 and 102 Medium Hardener were used for bonding, following the manufacturer's recommended ratio of 100:28.4 g. Vibration simulation and modal testing were performed on kenaf turbine blades, with SHM tests comparing frequency-response function graphs between embedded and bonded MFCs, as well as between damaged and undamaged blades. Micro energy harvesting results revealed a 348% increase in voltage RMS for bonded MFC (117.3 mV) compared to embedded MFC (26.2 mV) in the 10 to 100Hz range, indicating superior energy harvesting performance. In SHM, normal blades with bonded MFC exhibited higher magnitudes than damaged blades with bonded MFC, and similar trends were observed for embedded MFC. This suggests that the SHM system effectively functions in the kenaf wind turbine blade system. The experiment results for energy harvesting application were supported by the findings in bonded MFC of normal blades, which showed the highest magnitude in induced electricity throughout the experiments, while embedded MFC exhibited lower magnitudes than bonded MFC.

In the active control of structural vibrations using piezoelectric material, the placement of sensors and actuators has considerable influence in the performance of the control system [29]. A bunch of research has proposed different methodologies to determine the optimal position of sensor/actuator on the host structure.

[29] introduced a parametric optimization method for optimal placement of MFC sensors/actuators on a structure. The approach involves maximizing a controllability index along the plate's length, from the clamped tip to the free tip, while maintaining width-cantered positioning. Structural analysis and controllability index recalculation are performed for each placement using Linear Quadratic Regulator (LQR) control to minimize vibrations. Optimal MFC positions for the first three modal shapes are determined: clamped end for the first mode, 0.15-0.2m from the left end for the second mode, and 0.25 m from the clamped end for the third mode. A research by [30] classifies optimal sensor/actuator placement methods into non-systematic (such as some intuitive ‘‘cut and try’’ placement techniques) and systematic optimization methods such as Simulated Annealing (SA), Tabu Search (TS), and Genetic Algorithms (GAs). This work also discussed the advantages and limitations of each method under the two broad classification. Finally, this work proposes an optimal placement strategy of piezoelectric sensor/actuator pairs using the maximum damping effect. The optimum location of the sensor/actuator is determined as the point where the structural damping index is maximum.

Another factor that affects the performance of MFC-based health monitoring system is adessive layer between the MFC and the host structure. The adhesive forms an interfacial layer of finite thickness between the MFC and host structure. The adhesive interface provides the necessary mechanical coupling needed to transfer the forces and strains between the MFC and the host structure [31]. To develop an effective structural health monitoring system using MFC as piezoelectric transducer, it is important to have a comprehensive understanding on the adhesive effects on the interaction of piezoelectric transducer with the host structure.

In structural health monitoring service using piezoelectric transducers such as MFC, piezoelectric components face external loads and temperature aging, potentially degrading the adhesive between piezoelectric elements and the host structure [31]. This degradation impacts the transmission of piezoelectric signals, making signal changes unreliable for monitoring. The adhesive properties, such as shear strength, thickness, and aging, play a crucial role in signal transmission and system reliability within SHM systems.

In recent years, numerous studies have explored wave propagation methods and electromechanical impedance techniques employing piezoelectric elements. Despite accounting for structural dynamics in theoretical analyses, many authors have overlooked the influence of the adhesive layer [32].

A study by [31] experimentally investigates the intricate relationship between types of adhesives, adhesive thickness, accelerated aging, and monitoring signals. The experiment utilizes three epoxy resin AB adhesives (AW106, E-30CL, and E-120HP) with bonding thicknesses of 0.01, 0.05, and 0.12 mm, subjected to an elevated temperature of 100 °C for 45 days. Employing a signal-based monitoring method, characteristic parameters are extracted. Results suggest that standard shear strength and adhesive thickness collectively influence the monitoring signal, with increased thickness potentially enhancing shear strength but negatively impacting signal propagation effectiveness. Elevated temperature induces a peak signal amplitude within the initial 10 to 15 days of aging, after which adhesive degradation leads to a decline in signal amplitude.

[32] conducted an experiment on piezoelectric elements monitoring structural health. They used 144 PZT elements with three adhesives on aluminium plates. Adhesive thickness varied from 10 to 40 µm, and measurements were taken from 50–600 kHz. Results showed that increasing adhesive thickness impacted electro-mechanical impedance and resonant frequency. Up to 40 µm, adhesive thickness significantly affected sensor signal amplitude. At 500 kHz, a 40-µm adhesive bond layer provided better mechanical coupling, while at 50 kHz, a thin bond layer was more effective. Elastic modulus of adhesive had a slight impact at lower frequencies but was more sensitive at higher frequencies.

4. MULTIPHYSICS MODELLING BOLT JOINT LOOSENESS MONITORING USING MFC

4.1. Properties of MFC

Macro Fiber Composites are composed of piezoceramic fibers, epoxy matrix and electrodes that have two different types of structures, giving the $\boldsymbol{d}_{31}$or $\boldsymbol{d}_{33}$ modes. The $\boldsymbol{d}_{31}$ mode has piezoelectric material polarized in the thickness direction normal to the fiber direction, thus the $\boldsymbol{d}_{31}$effect is dominating the actuation forces. However, the second type of mode, $\boldsymbol{d}_{33}$, is arranged in a specific manner such that the polarization of the piezoelectric material is along the piezo-fiber direction. Therefore, $\boldsymbol{d}_{33}$ mode can use the $\boldsymbol{d}_{33}$ effect for generation of actuation forces, which is usually much larger (about 2 times larger) than the $\boldsymbol{d}_{31}$ effect [33]. Additionally, actuation voltages for $\boldsymbol{d}_{31}$patches can be applied in the range from -60 to 360 V (with the electrode separation of 0.18 mm), while those for $\boldsymbol{d}_{33}$ patches can vary between -500 and 1500 V (with centre-to-centre interdigitated electrode spacing of 0.5 mm) [33].

Out the four mathematically equivalent forms of piezoelectric constitutive relations, the stress charge form is expressed as:

$$\{S\} = [s^D]\{T\} + [d]\{E\} \tag{1}$$

$$\{D\} = [d]^T\{T\} + [\varepsilon^T]\{E\} \tag{2}$$

where $\{T\}(6 \times 1)$=stress vector(N/m^2), $\{D\}$ (3×1)=electric flux density vector(C/m^2), $\{S\}(6 \times 1)$=elastic strain vector(m/m), $\{E\}(3 \times 1)$=electric field intensity vector$(\frac{V}{m}\, or \frac{N}{C})$, $[s^D](6 \times 6)$= compliance matrix which is the inverse of the stiffness matrix$(\boldsymbol{c_{ij}})$ (m^2/N), $[d](6 \times 3)$=piezoelectric strain matrix$(\boldsymbol{C/N})$ and $[\varepsilon^T](3 \times 3)$=dielectric matrix (evaluated at constant mechanical stress)(F/m).

Compliance Matrix $[\boldsymbol{s_{ij}}]$

The compliance is the functional representation of the mechanical properties of the MFC. It can be calculated using the four linear elastic engineering constants presented by the manufacturers [7] or derived by [34] into the standard stress–strain relations for a transversely isotropic material as shown in equation [3]:

$$s_{ij}^E = \begin{bmatrix} {}^{1}/_{E_{11}} & {}^{-v_{31}}/_{E_{11}} & {}^{-v_{31}}/_{E_{33}} & 0 & 0 & 0 \\ {}^{-v_{31}}/_{E_{11}} & {}^{1}/_{E_{11}} & {}^{-v_{31}}/_{E_{33}} & 0 & 0 & 0 \\ {}^{-v_{31}}/_{E_{33}} & {}^{-v_{31}}/_{E_{33}} & {}^{1}/_{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & {}^{1}/_{G_{31}} & 0 & 0 \\ 0 & 0 & 0 & 0 & {}^{2(1+v_{31})}/_{E_{33}} & 0 \\ 0 & 0 & 0 & 0 & 0 & {}^{2(1+v_{31})}/_{E_{33}} \end{bmatrix} \tag{3}$$

The mechanical properties of M8557-P1 MFC actuator from Smart Materials Corp are given in Table1.

Table 1. Mechanical Properties of M8557-P1

Parameters	$E_{33}(GPa)$	$E_{11}(GPa)$	$G_{31}(GPa)$	v_{31}	v_{13}
Derived by [34]	29.4	15.2	6.06	0.312	0.16
From [7]	30.336	15.857	5.515	0.31	0.16

where E is Young's modulus of the MFC material, G is shear modulus of the MFC material, v is Poisson's ratio of the MFC material and subscripts denote the orientation of each property.

After substituting the values of the parameters in Table 1 into equation [3], the compliance matrix of M8557-P1 is given by equation [4].

$$s_{ij}^E = \begin{bmatrix} 0.065 & -0.0205 & -0.0106 & 0 & 0 & 0 \\ -0.0205 & 0.065 & -0.0106 & 0 & 0 & 0 \\ -0.0106 & -0.0106 & 0.034 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.165 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.173 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.173 \end{bmatrix} \times 10^{-9} m^2 N^{-1} \tag{4}$$

The corresponding command scripts in Ansys Mechanical is given by:

```
TB, ANEL,1,,,1 ! Elastic compliance matrix
TBDATA,1,0.065E-9,-0.0205E-9,-0.0106E-9
TBDATA,7,0.065E-9,-0.0106E-9
TBDATA,12,0.034E-9
TBDATA,16,0.165E-9
TBDATA,19,0.173E-9
TBDATA,21,0.173E-9
```

Piezoelectric Matrix

As described by several investigators the relationships between the piezoelectric properties of the constituent materials and the complete MFC are highly complex due to non-uniform polarisation of PZT fibres and the composite structure of the actuator and still subject of research efforts [35]. Based on the assumptions and simplifications made by [35], the piezoelectric strain constant and the relative permittivity of M8557-P1 are given by in matrix form as:

$$d_{ij} = \begin{bmatrix} -2.1 & 0 & 0 \\ -2.1 & 0 & 0 \\ 4.67 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times 10^2\ pmV^{-1},\ [\varepsilon^S] = \begin{bmatrix} 712 & 0 & 0 \\ 0 & 1.7 & 0 \\ 0 & 0 & 737 \end{bmatrix} \tag{5}$$

The corresponding command scripts in Ansys Mechanical is given by:

```
tb, piez, MATID,,,1
tbdata,1, -210     !d31
tbdata,4,-210     !d32
tbdata,7,467     !d33
mp,perx,MATID,712   ! dielectric permittivity x
mp,pery,MATID,1.7  ! dielectric permittivity y
mp,perz,MATID,737   ! dielectric permittivity z
```

4.2. Multiphysics Modelling

An integrated smart structure approach to monitoring the condition of Bolted Joint is modelled and simulated using ANSYS® 2021 R2 software. Two similar Micro-fiber composites (MFCs) are bonded to two aluminium plates connected by bolt, nut and washer assembly as shown in Figure1. One of the MFCs is used as an exciter to induce mechanical vibration to the structure. The second MFC measures a corresponding voltage due to the mechanical vibration of the structure.

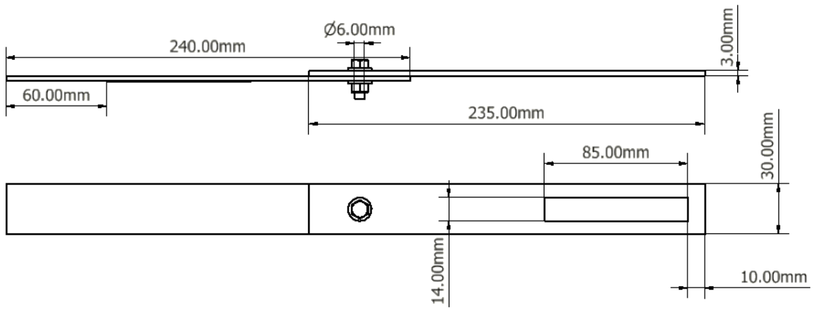

Fig. 1. 2D model of bolt joint assembly with integrated MFCs

Contact conditions

The system's stiffness varies based on the contact status, influenced by forces applied. Proper solver formulation and suitable contact types between mating elements can minimize the likelihood of contact and target face penetration. The model incorporates seven contacts, employing frictional with coefficient of friction 0.15, bonded, and no-separation interactions, along with Augmented Lagrange and Multi-Point Constraint (MPC) formulations (refer to Table 2).

Table 2. Contact Definition of the Model

Sr.No	Target	Contact	Type of interaction	Coefficient of Friction	Formulation
1	Plate-2	Plate-1	Frictional	0.15	AL
2	Plate	MFC	Bonded	------	AL
4	Bolt	Nut	No-Separation	------	MPC
5	Bolt	Washer	Frictional	0.15	AL
6	Nut	Washer	Frictional	0.15	AL
7	Plate	Washer	Frictional	0.15	AL

Meshing

In Finite Element Analysis (FEA), precise formulation of elements significantly impacts simulation outcomes. Employing the Hex Dominant method with Quad/Tri mesh type and a mesh size of 3mm, all components of the joint structure except the MFC transducers were meticulously meshed. The two MFC transducers were represented by 20-node quadratic brick SOLID226 elements.

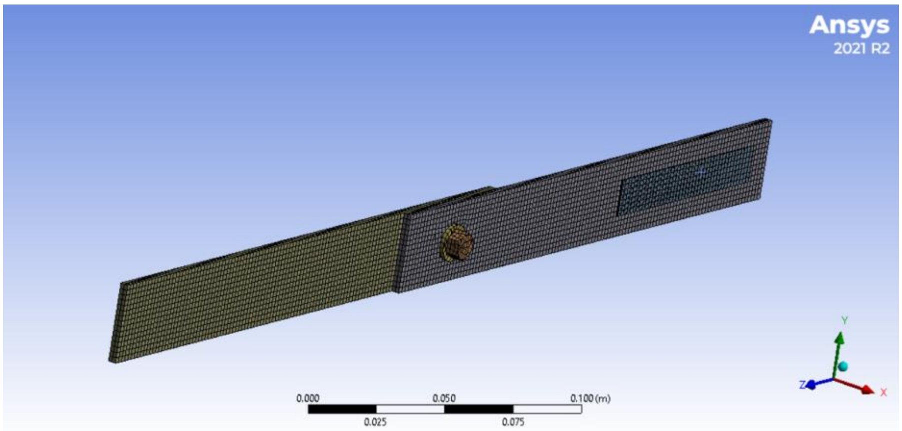

Fig.2. Model mesh result

Loading and Boundary Conditions

The fixed support restrains all degrees of freedom for nodes and elements on the outer left side surface of plate-1. During the tightening process using torque, the washer faces of both the bolt and nut serve as contact points, transmitting clamping force (Fc) to the target faces of the washers. This clamping force helps secure the plates together. Additionally, a preload force (Fp) is applied along the axial direction to the cylindrical surface of the bolt shank, as illustrated in Figure 3.

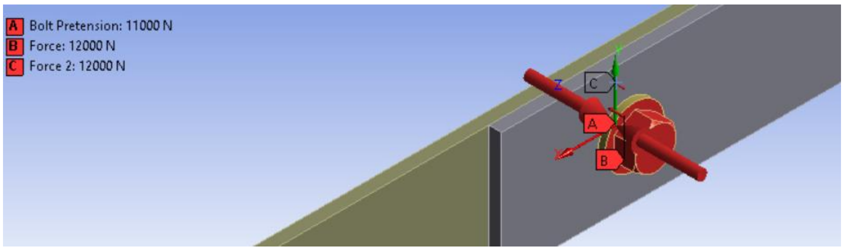

Fig.3. Loading definition on the joint.

5. RESULTS AND DISCUSSION

Pre-Stressed Modal Analysis was conducted at different loosening torque to detect effect of loosening torque by assuming 14.5Nm (12KN pretension load) is a full tightening torque.

Table 3. Pre-stressed modal analysis result for different loosening torque and the first six mode shapes

Preload(N)	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
1st N.freq(Hz)	14.415	14.535	14.575	14.582	14.583	14.584	14.584	14.585	14.585	14.586	14.588	14.59
2nd N.freq(Hz)	87.547	87.554	87.559	87.562	87.564	87.565	87.567	87.569	87.571	87.573	87.575	87.578
3rd N.freq(Hz)	133.29	133.41	133.5	133.55	133.6	133.64	133.66	133.68	133.7	133.72	133.74	133.76
4th N.freq(Hz)	253.71	253.87	253.93	253.94	253.95	253.96	253.97	253.98	253.99	254	254.01	254.02
5th N.freq(Hz)	370.77	375.1	379.8	382.73	385.09	386.88	387.68	387.76	387.81	387.87	387.96	388.07
6th N.freq(Hz)	513.17	513.2	513.23	513.25	513.27	513.28	513.3	513.32	513.34	513.36	513.39	513.42

In addition, pre-stressed Harmonic Analysis was conducted for different loosening torque to detect effect of loosening torque on the voltage measured by the second MFC(Sensor) at 14.583 and 87.567 Hz frequencies due to the vibration of the joint. The vibration of the joint was induced by the first MFC(Actuator) which was subjected by a sign voltage of 1500V amplitude. As mentioned before, 14.5Nm (12KN pretension load) was considered as full tightening torque.

Table 4. Pre-stressed harmonic analysis results for different loosening torque at 14.583 and 87.567 Hz frequencies

Preload (N)	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
Voltage(mV) @ 14.583Hz	1.90	2.069	2.1171	2.125	2.127	2.127	2.127	2.129	2.130	2.131	2.133	2.136
Voltage(mV) @ 87.564Hz	95.95	96.292	96.483	96.598	96.687	96.759	96.759	96.912	96.996	97.095	97.195	97.304

From pre-stressed modal analysis, as the preload increases to the corresponding value of full tightening torque (14.5Nm), the natural frequency increases. This satisfied the general theoretical principle that increasing bolt preload tends to increase joint stiffness. This increased stiffness can lead to a higher natural frequency. Higher natural frequencies often indicate a stiffer and more rigid joint. Conversely, the looser the connection, the lower the natural frequency of the structure. The natural frequency of a joint is a measure of how quickly it oscillates or vibrates when exposed to an external force or disturbance. From pre-stressed harmonic analysis, it has been observed that as the preload increases, the voltage measured by the sensor at both 14.583 and 87.567 HZ increases in magnitude. The voltage was measure at the positive electrode of the sensor. The voltage increase with respect to the preload is approximately linear.

6. CONCLUSIONS

In conclusion, this article offers a comprehensive exploration of the monitoring of bolt joint looseness and the optimization of MFC-based structures for applications like structural health monitoring. Pre-stressed modal analysis revealed that increasing preload towards full tightening torque led to higher natural frequencies, with values rising from 14.415 Hz at 1000N preload to 14.59 Hz at 12000N preload, in line with the expected trend of increased joint stiffness. Conversely, looser connections exhibited lower natural frequencies, with the frequency at 1000N preload being 14.415 Hz and at 12000N preload being 14.59 Hz, indicative of reduced rigidity. Pre-stressed harmonic analysis demonstrated a linear increase in voltage measured by the sensor as preload increased, with voltage values at 14.583 Hz frequency rising from 1.90 mV at 1000N preload to 2.136 mV at 12000N preload, and at 87.567 Hz frequency rising from 95.95 mV at 1000N preload to 97.304 mV at 12000N preload, suggesting a direct correlation between preload and voltage magnitude. The findings underscore the significance of MFC in efficient bolt joint health monitoring by overcoming the limitations of traditional piezoceramics and optimizing MFC-based smart structure manufacturing. The research also includes a succinct review of optimizing MFC-based smart structure manufacturing, focusing on attachment methods, optimal placement, and the crucial impact of adhesives. Overall, this study contributes valuable insights into the utilization of MFC as a versatile tool for real-time monitoring of mechanical joints and offering valuable insights into refining manufacturing processes for enhanced performance in SHM applications.

Conflicts of Interest: There is no conflict of interest.

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