ijrtsm

IJRTSM

INTERNATIONAL JOURNAL OF RECENT TECHNOLOGY SCIENCE & MANAGEMENT

# "BOLT LOOSENING DETECTION IN ALUMINIUM BOLTED PLATE STRUCTURES: A COMREHENSIVE REVIEW"

***Rajneesh Kushwaha* [1], *Dr. Girish Kumar Khare* [2]**

[1]M.Tech. *Scholar, Department of Mechanical Engineering, Oriental Institute of Science and Technology, Bhopal, India*
[2]*Professor, Department of Mechanical Engineering, Oriental Institute of Science and Technology, Bhopal, India*

## ABSTRACT

***Bolted joints are widely used in mechanical, aerospace, automotive, marine, railway, and structural engineering applications due to their ease of assembly, maintenance, and load transfer capability. However, these joints are highly sensitive to tightening torque, bolt preload, contact stiffness, frictional behaviour, and interface condition. During service, vibration, cyclic loading, impact, and transverse excitation may gradually reduce the bolt preload and initiate bolt loosening. Such loosening reduces the effective stiffness of the jointed structure and produces measurable changes in natural frequency, frequency response function, damping behaviour, vibration amplitude, and signal-based indicators. This review paper presents a systematic discussion on vibration-based bolt loosening detection in aluminium bolted plate structures, with special emphasis on experimental modal analysis and finite element approaches. The review covers the fundamentals of bolted joint dynamics, mechanisms of preload loss, influence of loosening on vibration response, experimental modal testing methods, finite element modelling strategies, vibration signal-based detection features, and recent structural health monitoring techniques. Experimental modal analysis is discussed as an effective method for obtaining natural frequencies, mode shapes, damping characteristics, and frequency response functions under healthy and loosened conditions. Finite element modelling is reviewed as a complementary tool for simulating preload variation, nonlinear contact behaviour, interface stiffness, and different bolt loosening scenarios. The review also highlights signal features such as signal energy, standard deviation, kurtosis, resonance peak shift, and FRF amplitude variation for loosening detection. It is observed that a combined experimental–numerical approach provides more reliable understanding of bolt loosening than either method alone. The paper further identifies major research gaps, including limited studies on Al 5052 bolted plate structures, challenges in nonlinear interface modelling, early-stage loosening detection, multi-bolt loosening identification, and real-time monitoring. The review concludes that validated finite element models combined with experimental modal data and vibration signal features can provide an effective framework for structural health monitoring of bolted aluminium plate assemblies.***

**Keywords:** *Bolted joint; Al 5052 plate; bolt loosening; vibration characteristics; experimental modal analysis; finite element analysis structural health monitoring.*

## I. INTRODUCTION

Bolted joints are among the most widely used mechanical fastening systems in engineering structures because they provide detachable, economical, and reliable connections between structural members. They are commonly used in aerospace panels, automobile frames, marine structures, railway systems, machine tools, pressure vessels, mechanical assemblies, and civil structures where periodic maintenance, replacement, and inspection are required. Unlike welded and riveted joints, bolted connections allow convenient disassembly; however, their dynamic performance strongly depends on bolt preload, tightening torque, frictional behaviour, contact stiffness, joint geometry, surface condition, and external loading environment [1][3]. In practical applications, these joints are frequently subjected to vibration, impact, transverse excitation, cyclic loading, and fluctuating environmental conditions. Such loading conditions may gradually reduce the initial bolt preload and initiate self-loosening, which can significantly reduce joint stiffness and compromise the safety of the complete structure [4][5].

Bolt loosening is particularly critical because it may not produce immediate visible damage, but it gradually changes the dynamic characteristics of the jointed structure. A reduction in preload weakens the clamping force between connected members and permits microslip, intermittent contact, fretting, and local stiffness degradation at the interface. As a result, measurable changes occur in natural frequency, damping ratio, frequency response function, vibration amplitude, and nonlinear dynamic behaviour [6][7]. If the loosening process remains undetected, it can lead to excessive vibration, noise, loss of alignment, fatigue crack initiation, structural instability, and catastrophic failure of mechanical systems. Therefore, early detection of bolt loosening has become an important research area in vibration-based structural health monitoring.

Aluminium alloys have gained considerable importance in modern lightweight structures due to their favourable strength-to-weight ratio, corrosion resistance, machinability, and suitability for transportation, marine, and aerospace applications. Among these alloys, Al 5052 is frequently used in plate-type structures because of its good corrosion resistance, formability, and mechanical performance. Bolted Al 5052 plate structures are therefore relevant in lightweight engineering systems where joint integrity and vibration reliability are essential. However, aluminium bolted joints may show significant sensitivity to preload variation because the interface behaviour, contact pressure distribution, and stiffness transfer between plates are strongly influenced by tightening conditions. For this reason, the vibration behaviour of bolted Al 5052 plate structures under different preload and loosening conditions requires systematic review and investigation.

Experimental modal analysis has been widely used for evaluating the vibration characteristics of bolted joint structures. In this method, the structure is excited using an impact hammer or shaker, and the vibration response is measured using accelerometers or other sensors. The acquired response is then processed to obtain frequency response functions, natural frequencies, damping behaviour, and mode shapes. Several studies have shown that bolt loosening can be detected from resonance frequency shift, variation in FRF amplitude, reduction in contact stiffness, and changes in damping characteristics [8][10]. However, experimental testing alone may not fully explain the interface-level mechanics of bolted joints, especially when nonlinear contact, friction, and preload-dependent stiffness are involved.

Finite element analysis provides a powerful numerical approach for simulating bolted joint dynamics. Three-dimensional finite element models can incorporate plates, bolts, nuts, contact surfaces, preload application, frictional contact, nonlinear interface behaviour, and boundary conditions. Software tools such as ABAQUS and ANSYS are commonly used to study modal response, nonlinear vibration behaviour, preload sensitivity, and loosening scenarios in bolted structures [11][13]. However, accurate modelling of bolted joints remains challenging because the dynamic response depends on uncertain parameters such as contact stiffness, friction coefficient, surface roughness, interface damping, preload distribution, and boundary constraints. Therefore, finite element model updating using experimental modal data is often required to improve the agreement between numerical and experimental results.

## II. FUNDAMENTALS OF BOLTED JOINT DYNAMICS

The dynamic behaviour of bolted joint structures is governed by the combined effect of mass, stiffness, damping, preload, friction, and interface contact conditions. When a bolt is tightened, tensile preload is generated in the bolt shank, which produces compressive clamping force between the connected members. This clamping force creates contact pressure at the interface and allows the jointed plates to behave like a nearly continuous structure. A sufficient preload improves contact stiffness, reduces relative motion between plates, and increases the stability of the assembled structure under dynamic loading [18], [19]. However, when the preload decreases, the contact pressure reduces and relative slip may occur at the joint interface. This causes a decrease in effective joint stiffness and produces nonlinear vibration behaviour.

The stiffness of a bolted joint is not only determined by the material properties of the plates and bolts but also by the contact behaviour of the interface. The contact zone between plates is usually non-uniform, and the actual contact area is much smaller than the apparent area due to surface roughness and asperity interaction. Under vibration, partial slip, microslip, and local separation may occur at the interface. These phenomena introduce nonlinear stiffness and damping into the system [20]. The nonlinear behaviour becomes more significant when the bolt preload is low or when the joint is subjected to transverse excitation. As a result, the vibration response of a bolted joint may not remain proportional to excitation force, and the resonance peaks may shift or broaden depending on the tightening condition.

Natural frequency is one of the most important modal parameters affected by bolt preload. In general, a properly tightened joint exhibits higher natural frequency because of higher contact stiffness. When bolt loosening occurs, the effective stiffness of the structure decreases, causing a reduction or shift in natural frequency. However, the relationship between preload and natural frequency is not always linear because contact stiffness changes nonlinearly with tightening torque and frictional conditions. In some cases, frequency shift may be small during early loosening stages, particularly when only one bolt is loosened or when the loosened bolt is located away from the dominant deformation region. Therefore, natural frequency alone may not always be sufficient for accurate loosening detection.

Frequency response function is another important tool for analysing the dynamic behaviour of bolted joints. FRF represents the relationship between input excitation and output vibration response as a function of frequency. Bolt loosening may cause changes in resonance peak location, peak amplitude, bandwidth, and phase response. A loosened joint generally shows increased vibration amplitude due to reduced stiffness and weaker energy transfer across the interface. The FRF may also show additional nonlinear features when intermittent contact or impact-like behaviour occurs between joint surfaces [21]. Therefore, FRF-based analysis is widely used in experimental modal testing and finite element validation of bolted joint structures.

Damping behaviour also plays a significant role in bolted joint dynamics. Mechanical joints are often major sources of structural damping because frictional energy dissipation occurs at the interface. When preload is sufficient, the contact surfaces remain tightly clamped, and energy dissipation is relatively stable. When preload decreases, microslip increases and damping may change significantly. In some cases, damping may initially increase due to frictional sliding but later become unstable due to intermittent contact and separation. This makes damping an important but complex parameter for bolt loosening detection [7], [18].

The vibration behaviour of bolted plate structures is also influenced by the number of bolts, bolt arrangement, plate thickness, overlap length, boundary condition, material type, and loading direction. Multi-bolt joints are more complex than single-bolt joints because preload loss in one bolt may redistribute load to neighbouring bolts. Uniform loosening affects the global stiffness of the structure, while single-bolt or alternate-bolt loosening creates local stiffness asymmetry. Group loosening may produce more severe dynamic changes because a larger portion of the joint interface loses contact stiffness. Therefore, different loosening scenarios must be considered when studying the vibration characteristics of bolted plate structures.

## III. BOLT LOOSENING MECHANISM AND ITS INFLUENCE ON VIBRATION RESPONSE

Bolt loosening is a progressive mechanical failure mechanism that occurs when the initial tightening force in a bolt decreases during service. The loosening process may be caused by vibration, transverse cyclic loading, impact, thermal expansion, material relaxation, embedment, surface wear, or insufficient tightening torque. Among these, vibration-induced self-loosening is one of the most common and critical causes of preload loss in bolted structures. When a joint is subjected to repeated transverse motion, relative slip may occur between the connected members and within the threaded contact surfaces. This slip can gradually rotate the nut or reduce the bolt tension, leading to preload loss [4][5].

The loosening mechanism is strongly associated with the balance between frictional resistance and external dynamic loading. In a properly tightened joint, friction at the thread and bearing surfaces resists relative movement. However, if dynamic loading exceeds the frictional resistance, microslip begins at the interface. With continued excitation, microslip may develop into macroslip, resulting in reduction of clamping force. Once the clamping force decreases, the joint becomes more flexible, and further vibration accelerates the loosening process. This feedback mechanism makes bolt loosening a serious problem in machines and structures exposed to continuous dynamic loading.

From a vibration perspective, bolt loosening can be considered a stiffness degradation problem. A tight bolted joint provides high contact stiffness because the connected plates are strongly compressed together. When a bolt becomes loose, the local contact pressure around that bolt decreases, and the interface becomes more compliant. This local reduction in stiffness affects the global vibration response of the structure. In plate-type assemblies, bolt loosening may cause reduction in natural frequency, increase in vibration amplitude, change in damping behaviour, and distortion of mode shapes [8][9]. The severity of these changes depends on the number of loosened bolts, the location of loosening, the level of preload reduction, and the mode shape being excited.

Single-bolt loosening generally produces localized stiffness reduction. Its effect may be clearly observed if the loosened bolt is located in a region of high modal deformation. However, if the loosened bolt is positioned near a nodal region of a particular mode shape, its influence on that mode may be small. Therefore, a single modal parameter may not detect all possible loosening cases. Multiple-bolt loosening produces more significant changes because a larger portion of the joint loses clamping force. Uniform loosening of all bolts causes global reduction in contact stiffness, while alternate-bolt loosening produces asymmetric stiffness distribution. Group loosening may cause the most severe vibration changes because several adjacent bolts lose their load-carrying contribution simultaneously.

Bolt loosening also influences damping behaviour. In the early stage of loosening, increased microslip may increase frictional energy dissipation, resulting in higher damping. However, as the joint becomes severely loose, intermittent contact and impact between surfaces may produce irregular vibration response. This can increase vibration amplitude and create nonlinear features such as harmonics, sidebands, and amplitude-dependent resonance behaviour. Such nonlinear effects are difficult to capture using only linear modal parameters, which is why modern studies often combine modal analysis with time-domain and frequency-domain signal features.

Time-domain vibration features are useful for identifying changes caused by loosened bolts. Signal energy represents the total vibration intensity and usually increases when the joint becomes loose due to reduced stiffness and higher response amplitude. Standard deviation indicates amplitude fluctuation and can reflect irregular vibration caused by unstable contact. Kurtosis is sensitive to impulsive behaviour and may increase when intermittent contact, impact, or sudden slip occurs at the joint interface. These features can supplement modal parameters and improve loosening detection accuracy.

Frequency-domain indicators are also widely used for bolt loosening detection. These include natural frequency shift, resonance peak variation, FRF amplitude change, spectral energy redistribution, and appearance of additional frequency components. A loosened joint may show lower resonance frequency due to stiffness loss and higher resonance amplitude due to reduced structural restraint. In some nonlinear cases, looseness may also generate higher harmonics or modulation effects. Therefore, frequency-domain analysis is particularly useful for identifying changes in structural stiffness and dynamic response.

## IV. EXPERIMENTAL MODAL ANALYSIS OF BOLTED PLATE STRUCTURES

Experimental modal analysis is a well-established method for determining the dynamic characteristics of mechanical and structural systems. It is widely used to evaluate natural frequencies, damping ratios, mode shapes, and frequency response functions of bolted joint structures. In the context of bolt loosening detection, experimental modal analysis is valuable because preload loss directly affects stiffness and damping, which are reflected in the measured vibration response. Therefore, modal testing provides a practical and nondestructive means of assessing the health condition of bolted joints.

In a typical experimental modal test, the structure is excited using an impact hammer or electrodynamic shaker, and the response is measured using accelerometers, laser vibrometers, or other vibration sensors. The input excitation and output response are processed to obtain the frequency response function. For bolted plate structures, impact hammer testing is commonly used because it is simple, cost-effective, and suitable for laboratory-scale modal analysis. The structure is often supported under free-free boundary conditions to minimize the influence of external constraints and to obtain its inherent dynamic properties [8], [10].

The quality of experimental modal analysis depends on several factors, including sensor placement, excitation location, boundary condition, signal sampling rate, frequency resolution, hammer tip stiffness, accelerometer mass, and noise level. In bolted plate structures, the excitation and response points should be selected carefully so that the important modes can be excited and measured effectively. If the excitation point is located near a nodal line of a mode, that mode may not appear clearly in the FRF. Similarly, improper accelerometer placement may reduce the sensitivity of the measured response to bolt loosening. Therefore, proper test planning is essential for reliable modal identification.

Experimental modal analysis helps detect bolt loosening by comparing modal parameters under healthy and loosened conditions. In a fully tightened joint, the plates remain firmly clamped and the structure exhibits relatively high stiffness. As bolt preload decreases, the contact stiffness at the interface reduces, causing changes in natural frequencies and FRF amplitudes. The resonance peaks may shift toward lower frequency, and the vibration response may become more pronounced. These changes can be used as indicators of joint degradation. However, the magnitude of frequency shift may be small in some cases, especially during early-stage loosening, which makes additional signal features necessary.

Damping estimation is another important aspect of modal testing. Bolted joints contribute significantly to structural damping due to frictional energy dissipation at the interface. Changes in preload modify the frictional condition and microslip behaviour, which affects damping. However, damping is more difficult to estimate accurately than natural frequency because it is sensitive to measurement noise, boundary condition, and nonlinear response. Despite this limitation, damping variation can provide useful information about interface behaviour and joint health.

Experimental modal analysis is also useful for validating finite element models. Since bolted joints involve complex contact and frictional behaviour, numerical models often require calibration or updating before they can accurately predict dynamic response. Experimental natural frequencies and FRFs can be used as reference data for finite element model updating. Model updating improves the numerical representation of uncertain parameters such as interface stiffness, contact damping, material properties, and boundary conditions. This integrated experimental–numerical approach is particularly useful for studying Al 5052 bolted plate structures, where preload-dependent contact behaviour must be represented accurately.

Several studies have shown that experimental modal analysis can successfully identify the influence of bolt tightening torque and preload loss on vibration behaviour. For example, experimental studies on bolted lap plates have demonstrated that natural frequencies and FRFs vary with tightening conditions, and that loosened bolts produce measurable changes in dynamic response [5], [8], [9]. Other studies have extended this approach by combining modal testing with finite element simulation, nonlinear interface modelling, or signal-based damage indicators [11]–[13]. These developments show that modal analysis is not only useful for basic vibration characterization but also for structural health monitoring of bolted joints.

## V. FINITE ELEMENT MODELLING OF BOLTED JOINT STRUCTURES

Finite element modelling has become one of the most important numerical tools for analysing the vibration behaviour of bolted joint structures. Since bolted joints involve complex contact interaction, preload generation, frictional sliding, local stiffness variation, and nonlinear interface behaviour, analytical methods alone are often insufficient to represent their real dynamic response. Finite element analysis allows researchers to model the geometry of plates, bolts, nuts, washers, contact surfaces, tightening conditions, and boundary constraints in a controlled numerical environment. Therefore, it is widely used to study the effect of bolt preload, joint stiffness, contact pressure distribution, and loosening conditions on modal characteristics and vibration response [3][11][14].

In bolted plate structures, a three-dimensional finite element model is generally preferred when accurate representation of contact and preload behaviour is required. The connected plates are usually modelled using solid elements, while bolts and nuts may be modelled either in detailed form or simplified form depending on the objective of the study. A detailed model includes bolt shank, head, thread region, nut, contact surfaces, and preload application. Although such models provide better physical representation, they require high computational cost. On the other hand, simplified models use beam elements, connector elements, spring elements, or equivalent stiffness representation to reduce computational time. The selection of modelling strategy depends on whether the study focuses on global vibration behaviour, local contact mechanics, or real-time structural health monitoring [9][20].

One of the most critical aspects of finite element modelling of bolted joints is the representation of contact interaction. The interface between the connected plates plays a major role in determining the stiffness and damping behaviour of the joint. Surface-to-surface contact formulation is commonly used to simulate interaction between plate surfaces, bolt head and plate, and nut and plate. Frictional contact is introduced to represent resistance against relative sliding. The friction coefficient significantly affects the distribution of contact pressure and tangential stiffness. Since bolt loosening is strongly associated with loss of contact pressure and increased slip at the interface, accurate contact modelling is essential for reliable vibration prediction [7][11].

Bolt preload is another important modelling parameter. In finite element software such as ABAQUS, preload can be applied using bolt-load options or equivalent thermal/mechanical loading methods. The applied preload represents the tensile force generated in the bolt during tightening. A properly applied preload creates compressive contact pressure between the plates and increases the effective stiffness of the joint. When preload is reduced in the numerical model, the joint becomes more flexible, and changes in natural frequency, frequency response amplitude, and damping behaviour can be observed. This makes finite element analysis highly useful for simulating different loosening scenarios, including single-bolt loosening, multiple-bolt loosening, alternate-bolt loosening, and uniform preload loss [14].

Mesh convergence is also necessary for obtaining reliable finite element results. A coarse mesh may fail to capture stress concentration, contact pressure distribution, and interface behaviour accurately, while an excessively fine mesh increases computational cost. Therefore, mesh convergence analysis is generally performed by comparing natural frequencies or other response parameters at different mesh sizes. Once the variation in modal response becomes negligible with further mesh refinement, the selected mesh is considered suitable for dynamic analysis. In bolted plate structures, mesh refinement is especially important near bolt holes, contact regions, and overlap zones because these areas strongly influence joint stiffness and vibration response.

Finite element model updating is often required because numerical models contain uncertainties related to material properties, contact stiffness, friction coefficient, damping, and boundary conditions. Experimental modal data can be used to update the numerical model so that the predicted natural frequencies and FRFs agree more closely with measured results. In the case of bolted joints, updating may involve adjustment of interface stiffness, contact parameters, damping coefficients, elastic modulus, or preload-related parameters. Model updating improves confidence in the numerical model and allows it to be used for further parametric studies and loosening simulations [3][12][14].

## VI. VIBRATION SIGNAL-BASED BOLT LOOSENING DETECTION METHODS

Vibration signal analysis is widely used for detecting bolt loosening because loosening directly affects the dynamic response of a structure. When bolt preload decreases, the joint loses stiffness and the vibration signal shows measurable changes in amplitude, frequency content, damping, and statistical features. These changes can be extracted from time-domain, frequency-domain, and time-frequency-domain signals. Therefore, vibration-based indicators are useful for structural health monitoring of bolted joints, especially when direct measurement of bolt preload is difficult during service [6][10][15].

Time-domain analysis involves the direct examination of vibration response signals. Common time-domain features include peak amplitude, root mean square value, standard deviation, signal energy, skewness, and kurtosis. Signal energy represents the overall vibration intensity of the structure. A loosened joint generally shows higher vibration energy because reduced contact stiffness allows larger vibration amplitude. Standard deviation indicates the degree of amplitude fluctuation in the response signal. If the joint becomes loose, the vibration response becomes more irregular, causing an increase in standard deviation. Kurtosis is especially useful for detecting impulsive behaviour. In severely loosened joints, intermittent contact, impact, and sudden slip may occur at the interface, which may increase kurtosis.

Frequency-domain analysis is also highly effective for bolt loosening detection. In this approach, vibration signals are transformed into the frequency domain to identify changes in natural frequency, resonance peak amplitude, spectral energy, and frequency response function. A reduction in preload generally decreases joint stiffness, which may shift resonance frequencies toward lower values. The FRF amplitude may increase due to reduced structural constraint. In some cases, loosened bolts may also generate additional frequency components because of nonlinear contact and impact-like behaviour. Therefore, natural frequency shift and FRF variation are commonly used indicators in experimental modal analysis of bolted joints [8][10][14].

Time-frequency analysis is useful when the vibration response is non-stationary. Since bolt loosening may produce intermittent contact and sudden changes in signal characteristics, methods such as wavelet transform, short-time Fourier transform, empirical mode decomposition, and Hilbert–Huang transform have been explored in structural health monitoring. These methods help identify transient features that may not be clearly visible in ordinary time-domain or frequency-domain analysis. Guided wave techniques have also been used to detect loosening because wave propagation is sensitive to contact condition, preload, and interface stiffness [2][6].

Impedance-based methods are another important category of bolt loosening detection technique. These methods use piezoelectric sensors to measure the electromechanical impedance response of a structure. Since local stiffness changes influence impedance signatures, bolt loosening can be detected by comparing impedance changes between healthy and loosened conditions. Such methods are useful for local damage detection and may require only a small amount of training data when combined with probabilistic or machine learning techniques [15].

Machine learning and artificial intelligence have recently been introduced for automatic bolt loosening detection. In these approaches, vibration features are extracted from measured signals and used to train classification or regression models. Algorithms such as support vector machines, artificial neural networks, probabilistic neural networks, random forests, and deep learning models can classify different loosening levels or predict residual torque. These methods are useful when large signal datasets are available. However, their accuracy depends on the quality of training data, feature selection, sensor placement, and experimental conditions. Therefore, machine learning-based loosening detection should be supported by physically meaningful vibration features and validated experimental data.

For bolted Al 5052 plate structures, signal features such as natural frequency shift, FRF amplitude, signal energy, standard deviation, and kurtosis are especially relevant because they are directly related to stiffness reduction and irregular vibration caused by loosened bolts. A combined feature-based approach is more reliable than using a single indicator. For example, natural frequency shift may detect global stiffness reduction, while kurtosis may detect local impact-like behaviour. Similarly, FRF amplitude may show resonance response changes, while signal energy can quantify vibration intensity. Therefore, multi-feature vibration analysis provides a stronger basis for bolt loosening detection.

## VII. CONCLUSIONS

This review paper discussed the vibration characteristics and bolt loosening detection methods for bolted aluminium plate structures, with special emphasis on experimental modal analysis and finite element approaches. Bolted joints are essential in many engineering systems, but their performance is strongly affected by bolt preload, contact stiffness, frictional behaviour, damping, and interface condition. Loss of preload due to vibration-induced self-loosening can reduce joint stiffness and produce measurable changes in natural frequency, frequency response function, vibration amplitude, damping behaviour, and statistical signal features.

The review shows that experimental modal analysis is a practical and effective method for studying the dynamic behaviour of bolted plate structures. Impact hammer testing, accelerometer-based response measurement, and FRF analysis can identify changes in modal parameters caused by bolt loosening. However, experimental methods alone may not fully explain the internal contact mechanics of the joint. Therefore, finite element simulation is required to study preload variation, contact pressure distribution, interface stiffness, and different loosening scenarios.

Finite element modelling provides a powerful tool for simulating bolted joint behaviour under different tightening and loosening conditions. However, accurate modelling requires proper representation of contact, preload, friction, mesh convergence, and nonlinear interface behaviour. Since numerical models contain uncertainties, experimental validation and model updating are essential for reliable prediction. The combined experimental–numerical approach offers a strong framework for analysing Al 5052 bolted plate structures.

Vibration signal-based indicators such as natural frequency shift, FRF amplitude, signal energy, standard deviation, kurtosis, and damping variation are useful for detecting bolt loosening. A multi-feature approach is more reliable than a single indicator because different features respond differently to preload loss and contact nonlinearity. Recent developments in impedance-based sensing, guided waves, machine learning, and smart monitoring systems further enhance the possibility of real-time bolt loosening detection.

## REFERENCES

[1] Z. Qin, Q. Han, and F. Chu, “Bolt loosening at rotating joint interface and its influence on rotor dynamics,” Engineering Failure Analysis, vol. 59, pp. 456–466, 2016.

[2] Z. Zhang, M. Liu, Z. Su, and Y. Xiao, “Quantitative evaluation of residual torque of a loose bolt based on wave energy dissipation and vibro-acoustic modulation: A comparative study,” Journal of Sound and Vibration, vol. 383, pp. 156–170, 2016.

[3] P. Langer, K. Sepahvand, C. Guist, and S. Marburg, “Finite element modeling for structural dynamic analysis of bolted joints under uncertainty,” Procedia Engineering, vol. 199, pp. 954–959, 2017.

[4] Z. Qin, D. Cui, S. Yan, and F. Chu, “Application of 2D finite element model for nonlinear dynamic analysis of clamp band joint,” Journal of Vibration and Control, vol. 23, no. 9, pp. 1480–1494, 2017.

[5] X. Liao, J. Zhang, X. Xu, and C. Zhang, “Dynamic response analysis in bolted joint structure with viscoelastic layer and experimental investigations,” Journal of Vibroengineering, vol. 19, no. 3, pp. 1585–1596, 2017.

[6] F. Du, C. Xu, H. Ren, and C. Yan, “Structural health monitoring of bolted joints using guided waves: A review,” Structural Health Monitoring and Sensor Processing, vol. 163, pp. 45–67, 2018.

[7] J. Armand, L. Salles, C. W. Schwingshackl, D. Süß, and K. Willner, “On the effects of roughness on the nonlinear dynamics of a bolted joint: A multiscale analysis,” European Journal of Mechanics - A/Solids, vol. 70, pp. 44–57, 2018.

[8] M. A. Beaudoin and K. Behdinan, “Analytical lump model for the nonlinear dynamic response of bolted flanges in aero-engine casings,” Mechanical Systems and Signal Processing, vol. 115, pp. 14–28, 2019.

[9] R. Omar, M. A. Rani, M. Yunus, W. W. I. Mirza, and M. M. Zin, “Investigation into joint stiffness for finite element modelling of the dynamic behaviour of a structure with bolted joints,” IOP Conference Series: Materials Science and Engineering, vol. 530, Art. no. 012048, 2019.

[10] X. Chi, D. Di Maio, and N. A. J. Lieven, “Health monitoring of bolted joints using modal-based vibrothermography,” SN Applied Sciences, vol. 2, Art. no. 1106, 2020.

[11] D. Li, C. Xu, J. Kang, and Z. Zhang, “Modeling tangential friction based on contact pressure distribution for predicting dynamic responses of bolted joint structures,” Nonlinear Dynamics, vol. 101, no. 1, pp. 255–269, 2020.

[12] A. T. Mathis, N. N. Balaji, R. J. Kuether, A. R. Brink, M. R. Brake, and D. D. Quinn, “A review of

ISSN : 2455-9679
SJIF Impact Factor : 6.190

damping models for structures with mechanical joints," Applied Mechanics Reviews, vol. 72, no. 4, Art. no. 040802, 2020.

[13] M. Brøns, T. A. Kasper, G. Chauda, S. W. Klaassen, C. W. Schwingshackl, and M. R. Brake, "Experimental investigation of local dynamics in a bolted lap joint using digital image correlation," Journal of Vibration and Acoustics, vol. 142, no. 5, Art. no. 051007, 2020.

[14] P. Sharos and C. McCarthy, "Novel finite element for near real-time design decisions in multi-fastener composite bolted joints under various loading rates," Composite Structures, vol. 240, Art. no. 112075, 2020.

[15] A. Pirdayr, M. Mohammadi, M. J. Kazemzadeh-Parsi, and M. Rajabi, "Self-loosening effects on vibration characteristics of plates with bolted joints: An experimental and finite element analysis," Measurement, vol. 185, Art. no. 109922, 2021.

[16] W. S. Na, "Bolt loosening detection using impedance based non-destructive method and probabilistic neural network technique with minimal training data," Engineering Structures, vol. 226, Art. no. 111228, 2021.

[17] H. Li, H. Lv, H. Sun, Z. Qin, J. Xiong, Q. Han, J. Liu, and X. Wang, "Nonlinear vibrations of fiber-reinforced composite cylindrical shells with bolt loosening boundary conditions," Journal of Sound and Vibration, vol. 496, Art. no. 115930, 2021.

[18] J. Jiang, S. Zhang, Y. Li, and H. Wang, "Multi-bolt looseness state monitoring using the recursive feature elimination and machine learning approach," Measurement, vol. 193, Art. no. 110992, 2022.

[19] K. Jiang, X. Xie, Y. Zhang, and Z. Liu, "Capacitively-coupled dual ring antennas for bolt loosening detection," Measurement, vol. 187, Art. no. 110326, 2022.

[20] N. Chelimilla, V. Chinthapenta, N. Kali, and S. Korla, "Review on recent advances in structural health monitoring paradigm for looseness detection in bolted assemblies," Structural Health Monitoring, vol. 22, no. 6, pp. 4264–4304, 2023.

[21] W. Lei, Y. Zhang, X. Liu, and J. Chen, "Vision-based real-time bolt loosening detection by deep learning and image processing," Sensors, vol. 24, no. 20, Art. no. 6574, 2024.

[22] L. Yuan, M. Sun, G. Yan, K. Que, B. Wang, S. Xu, Y. Lian, and Z. Tang, "Experimental study on loosening and vibration characteristics of vibrating screen bolts of combine harvester," Agriculture, vol. 15, no. 7, Art. no. 749, 2025.