# Influence of Elemental Composition in Metals on their Vibration Performance: A Review

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**Abstract**

The vibration performance of metal beams plays a critical role in many engineering applications, including structural, aerospace, and mechanical systems. This review paper aims to investigate how variations in the constituent elements of metals affect their behaviour under vibration loading. Through a careful analysis of existing literature, the paper discusses the different methodologies used by researchers to study this relationship, ranging from analytical models to numerical simulations and experimental testing. Variations in the type and concentration of elements such as carbon, nickel, chromium, and others significantly affect stiffness, damping capacity, and natural frequencies of metals, which in turn influence their vibration performance. The paper also examines how welding, often necessary in metal structures, is affected by vibration loading. Metals operating in high-temperature environments tend to undergo microstructural changes such as grain growth, phase transformations, and precipitate coarsening, which can degrade their vibration performance over time. This review provides a consolidated understanding of how material composition, welding conditions, and thermal effects collectively influence the vibration performance of metal beams.

## 1. Introduction

In current work, the literature review is presented in the sequence of paper study. The next criteria used is the methodology adopted by the research community in the said domain.

A deeper understanding of vibration-assisted techniques and their influence on low-carbon steel has been made possible by recent experimental advancements. While each study offers a distinct experimental approach, they collectively enrich the knowledge surrounding how vibrational energy impacts material properties—particularly internal friction, residual stress, and deformation behaviour. A comparative view through methodological lenses reveals their convergence and divergence across the spectrum of vibration-induced responses. In the study by Meng et al. (2022), the influence of low-frequency vibration (50 Hz) on low-carbon steel DC04 during upsetting deformation was extensively explored to reveal a vibration softening effect. The authors used an experimental setup involving a servo-motor-driven eccentric shaft that applied controlled vibrational amplitudes (small, medium, and large) to steel specimens during uniaxial compression. The outcomes demonstrated a clear inverse relationship between vibration amplitude and forming load: stress reductions reached up to 46.7% under large amplitude excitation. EBSD and optical microscopy revealed grain boundary misorientation and intensified deformation, indicating enhanced plastic flow. Furthermore, the study introduced a novel softening model incorporating energy transfer efficiency. The deformation was not homogenous, and uneven distribution of residual stresses was observed post-compression—interpreted as an illusion of residual softening. This detailed experimental framework provides strong evidence that controlled vibration not only reduces forming resistance but also alters microstructural evolution in a measurable way (Meng et al., 2022).

Complementing this, Lai et al. (2020) took a dynamic mechanical analytical (DMA) approach to study vibratory stress relief (VSR) in low-carbon steel (DC01), investigating how internal friction evolved under varying frequencies and amplitudes. This work delved into the *atomic-level interactions*, suggesting that higher amplitudes induce greater lattice motion and dislocation activity. Their DMA-based cantilever bending tests identified optimal frequencies (37 Hz and 85 Hz) at which internal friction peaked — corresponding to improved stress-relief ratios (up to 82.2%). However, excessive vibration (e.g., at 400 μm amplitude) initiated fatigue and micro-crack formation. Their results highlighted a critical threshold: while higher amplitudes improve stress relief, surpassing a limit causes structural instability. Intriguingly, internal friction — usually a by-product of dislocation motion — was proposed as a diagnostic tool for fatigue crack nucleation. This study reinforces the importance of amplitude-frequency optimization in VSR applications, particularly for fatigue-sensitive structures (Lai et al., 2020). Meanwhile, Zhou et al. (2018) investigated modal properties of aluminum alloy and mild steel beams under varying vibration modes, blending experimental modal analysis with finite element simulation. Their research revealed how material stiffness, boundary conditions, and geometry govern natural frequency distributions. Although the beam materials differ from the steel grades in the other two studies, this paper complements the broader vibration theme by focusing on how materials like mild steel respond in a modal context. Experimental observations showed that mild steel exhibited lower natural frequencies than aluminium, owing to higher density and stiffness. The experimental-numerical agreement was strong, particularly in low modes. Their approach underlines how numerical models validated with physical testing are indispensable in predicting vibration responses of beams, crucial for design in aerospace and automotive structures (Zhou et al., 2018).

These three papers, although distinct in their methodologies — Meng et al. employing direct deformation under vibration, Lai et al. focusing on internal damping behaviour, and Zhou et al. analysing beam resonance — are unified by their focus on vibration as a modifier of mechanical performance in metallic systems. While Meng and Lai target microstructural and stress responses, Zhou emphasizes dynamic behaviour and modal validation**.** Together, they demonstrate that whether through internal friction metrics, force-displacement responses, or frequency spectrum shifts, vibration analysis across scales and setups can unlock transformative improvements in structural design, manufacturing, and fatigue life optimization**.**

Each work in existing literature employs a unique lens — ranging from tensile testing to acoustic signal capture — yet they converge in exploring how vibration interacts with mechanical response, energy dissipation, and performance quality of steel-based components. Meng et al. (2017) explored the impact of low-frequency vibration (15–50 Hz) during tensile deformation of low-carbon steel (DC04), using a high-precision tensile testing system coupled with a mechanical shaker. Their investigation focused on the softening effects induced by vibration during deformation and after unloading. By systematically varying vibration frequency, amplitude, and pre-strain levels, they observed an immediate drop in tensile load when vibration was applied and a persistent stress reduction post unloading. Through EBSD imaging, they attributed this residual softening to dislocation annihilation and rearrangement, rather than permanent damage. Notably, the softening was more pronounced at lower frequencies and higher amplitudes. This work reinforced the notion that vibrational energy, when properly tuned, facilitates easier dislocation motion and deformation, thus improving metal formability and reducing required forming forces. The study's dual-time-scale analysis — focusing on real-time effects and post-vibration consequences — adds depth to vibration-assisted forming research, especially for applications demanding high ductility and precision. In contrast, Tyč et al. (2022) applied vibration monitoring for process diagnostics in abrasive water jet (AWJ) cutting of mild steel (W. Nr. 1.0038). Rather than altering the material's mechanical response, their goal was to observe vibration signals to infer process quality. Three piezoelectric accelerometers were mounted at strategic points near the cutting zone to record vibrations in three axes, especially focusing on the root mean square (RMS) values. The authors tested variations in nozzle distance, abrasive mass flow, and feed rate to simulate cutting defects such as undercuts and partial separations. They discovered that tangential vibrations correlated directly with cutting quality, with lower RMS values indicating successful cuts and higher values flagging defects. Particularly, horizontal (x-axis) acceleration provided the clearest indicator. The strength of this study lies in its pragmatic application: it presents vibration signal monitoring as a non-invasive, real-time quality control tool, eliminating the need for visual inspection. The research demonstrates how vibrational behaviour, when interpreted statistically, can act as a signature of hidden process instabilities.

### 1.2 Application of Statistical Techniques adopted by researchers

Further extending the scope, Aherwar et al. (2014) carried out a statistical and regression-based analysis of cutting tool vibration during turning of EN24 steel using carbon steel tools. This study focused on the interplay between cutting parameters — cutting speed, depth of cut, and feed rate—and the resultant axial and tangential tool vibrations. Using a Taguchi L9 orthogonal array, they conducted experiments on a centre lathe while varying the input conditions systematically. The vibrational response was captured via dual-axis vibrometers, and RMS values were analysed using ANOVA and signal-to-noise (S/N) ratios. Results revealed that cutting speed had the highest influence, contributing over 93% to vibration amplitude in both directions. The authors developed regression models to predict vibration behaviour and verified their accuracy through confirmation runs. This work not only quantified the significance of machining parameters on vibration but also highlighted the benefits of design of experiments (DOE) and signal analysis in optimizing process stability and tool life.

Across these three studies, we observe an evolving trend: while Meng et al. use vibration as an assistive mechanism for improving formability, Tyč et al. treat vibration as a diagnostic signal, and Aherwar et al. focus on vibration as a dependent variable driven by machining conditions. The common thread remains the precise experimental control and quantitative interpretation of vibration, underscoring its multi-functional role in modern steel processing—from form enhancement to fault detection and process optimization.

Few research papers employ unique methodologies such as ranging from hole reaming to structural model updating and they collectively emphasize how vibration control can influence precision, accuracy, and structural behaviour across manufacturing stages. Ali et al. (2022) conducted an experimental study on ultrasonic vibration reaming (UVR) of C45 medium carbon steel, focusing on surface quality and circularity of machined holes. The study imposed ultrasonic vibrations (20 kHz frequency and 0.01 mm amplitude) onto a reamer during cutting. Parameters such as cutting speed, feed rate, and reaming depth were varied to assess their effects on surface roughness and circular degree. Results showed a consistent improvement in surface finish and dimensional precision compared to conventional reaming. The vibrational energy helped reduce cutting temperature and force, which contributed to enhanced tool life and decreased thermal deformation. The average roughness dropped significantly at moderate cutting conditions, and the maximum deviation in circularity was found to be minimal (around 0.003 mm). The study highlights UVR as a viable technique for precision applications, particularly in aerospace and medical devices. Its significance lies in demonstrating how superimposed high-frequency vibration not only assists in material removal but also stabilizes the machining environment, providing a superior surface and dimensional control. Meanwhile, Sani et al. (2017) analysed the dynamic behaviour of resistance spot welded (RSW) joints between dissimilar metals—mild steel 1010 and stainless steel 304—using finite element analysis (FEA) and experimental modal analysis (EMA). The goal was to quantify the discrepancy in natural frequencies between modelled and experimental responses and then update the finite element model via sensitivity-based model updating. Vibration modes were experimentally captured using impact hammer testing and compared to simulated values from MSC Nastran. The initial frequency deviation was under 10%, and after updating material properties—specifically Young’s modulus and density of both base metals—the average error reduced significantly. This cross-validation enhanced the model’s predictive accuracy. This work is noteworthy for illustrating the challenges and benefits of modal correlation in welded steel structures, especially in automotive or rail applications where dynamic stiffness is critical. The study reveals how material heterogeneity and welding effects can be compensated through modal updating, offering valuable insights for improving structural simulations in complex joints.

Complementing the mechanical experiments, Nagarjuna and Sudhakar (2021) applied ultrasonic vibrations in the turning process of medium carbon steel AISI 1040, comparing dry and flooded conditions to understand thermal and vibrational impacts. Ultrasonic vibration-assisted turning (UVAT) was conducted using a custom setup that integrated a piezoelectric actuator to oscillate the tool in the vertical direction. Under dry conditions, a clear reduction in both temperature rise and amplitude of vibration was recorded compared to conventional turning. The influence of ultrasonic frequency helped reduce friction, which minimized heat generation and enhanced surface quality. The flooded environment further aided in dissipating heat, but the synergy of ultrasonic vibration and dry conditions offered optimal thermal stability and tool control. Notably, the amplitude of vibrations dropped significantly in the UVAT setup, confirming the method's efficacy in enhancing process damping. The work contributes critical findings in reducing tool wear and improving dimensional accuracy, positioning ultrasonic assistance as a sustainable alternative in machining hard steels with reduced lubrication requirements. Together, these studies exhibit a common trajectory — leveraging high-frequency vibrations either to enhance machining precision or refine structural behaviour. Whether embedded into the tool as in UVAT and UVR, or observed as a dynamic signature in welded assemblies, vibration becomes both a tool and a diagnostic parameter, crucial to advancing precision engineering in metallic structures.

### 1.3 The Role of Software Tools in Analytical and Numerical Treatment

The role of vibration in assessing fatigue performance of steel-based automotive components continues to evolve from pure experimental inquiry to sophisticated simulation and data-driven frameworks. In their 2022 study, Rakesh et al. focused on the finite element-based vibration and modal analysis of leaf springs made from SAE 5160 carbon steel, a widely used material in automotive suspension systems. The authors constructed a 3D CAD model of the spring using CATIA and imported it into ANSYS Workbench for both static structural and modal analysis. By constraining one end and applying a force on the other, the team examined the stress distribution, deformation characteristics, and corresponding natural frequencies. The simulation revealed a maximum equivalent (von Mises) stress of 202.7 MPa under the applied load, well below the material's yield limit, thus indicating a safe design margin. Modal analysis uncovered the first six natural frequencies ranging from 238 Hz to 1932 Hz, each accompanied by distinct mode shapes including lateral, torsional, and axial modes. The authors emphasized how accurate prediction of resonant frequencies is crucial to avoid amplification and premature failure during service. Their numerical methodology offers an efficient and cost-effective alternative to physical vibration testing, especially in early design validation. Furthermore, the integration of static and modal results allowed the team to correlate deformation behaviour with vibrational response, offering a holistic assessment of structural integrity under dynamic loads. While the study didn't incorporate experimental validation, it sets a solid foundation for further work in combined simulation and physical fatigue life prediction. Complementing this is the comprehensive experimental-numerical work by Kong et al. (2018), who investigated the vibration fatigue life of a carbon steel coil spring under real-world road excitations. Using SAE 5160 medium carbon steel as the material of study, they adopted both strain gauge and accelerometer instrumentation to monitor fatigue responses as a passenger car traversed rural, residential, and highway terrains. The acceleration signals were converted into power spectral densities (PSD), and several PSD-based cycles counting methods — Dirlik, Lalanne, and Narrow Band — were applied to predict fatigue life using the stress-life (S-N) approach. The Dirlik method showed the closest correlation to actual strain-based fatigue measurements, highlighting its robustness in handling non-stationary and broad-band excitation data. Finite Element Analysis (FEA) of the spring structure further helped extract modal frequencies and corresponding mode shapes, revealing critical resonance at 458 Hz in the axial mode. Notably, the rural road condition caused the highest RMS acceleration and strain, leading to the shortest fatigue life ($4.47 \times 10^7$ cycles to failure), whereas the highway profile produced minimal stress amplitudes and thus longer life expectancy. The strength of this study lies in its fusion of real-world vibration signals, frequency domain transformation, and modal correlation, making it one of the few works to rigorously validate simulation-based fatigue estimates against physical strain data. The authors also noted the statistical significance of kurtosis and RMS values of vibration signals, which influenced fatigue damage accumulation. Overall, the work showcases a highly effective protocol for spring durability evaluation and paves the way for replacing expensive full-scale tests with data-driven predictive models. While Rakesh et al. provide a controlled numerical perspective on modal risk zones in leaf springs, Kong et al. extend this into the stochastic domain, tackling random road excitations with experimental realism. Together, they mark a progressive shift toward simulation-informed fatigue diagnostics, where dynamic behaviour is predicted, monitored, and interpreted through multi-domain analytical convergence.

In the next study by Palani and colleagues (2020), the authors examined the fatigue performance of 1100 aluminum alloy cantilever beams under random vibrational loading using a shaker test rig with an accelerometer and strain gauge instrumentation. The experimental setup featured a cantilever beam fixed at one end and exposed to broadband Gaussian random vibration signals. The primary aim was to analyze vibration response using frequency domain fatigue analysis techniques, particularly employing Power Spectral Density (PSD) and the Dirlik method for damage prediction. Time histories of strain were transformed into PSDs, and fatigue damage was computed using the Rainflow cycle counting method coupled with Miner's rule. The study demonstrated that random vibration loading generated high-cycle fatigue failures in the aluminum beam, with damage accumulation becoming significant in resonance regions. The authors emphasized the importance of modal analysis in identifying critical frequencies, observing that the second bending mode at 458 Hz produced the most severe strain response. Furthermore, the experiments showcased how aluminum's relatively low fatigue limit made it particularly susceptible to vibratory damage under high-frequency excitation. Importantly, the authors correlated analytical predictions with observed failures, establishing a foundational link between real-time strain data and frequency domain fatigue estimations. This study exemplifies a robust experimental methodology for evaluating lightweight alloys under service-like vibratory conditions. In contrast, Khalij et al. (2015) presented a highly sophisticated vibrational fatigue characterization of low carbon steel beams using an electrodynamic shaker with closed-loop adaptive control. Their objective was to establish high-cycle fatigue curves ($\varepsilon$–$N_f$) for steel specimens subjected to bending vibrations at frequencies near resonance (~100 Hz). The methodology integrated strain gauge-based strain amplitude tracking and modal parameter monitoring, including resonant frequency and damping factor variations, to assess damage progression. The specimens—cantilever beams heat-treated for microstructural uniformity—were cyclically tested while transmissibility functions were logged every $10^4$ cycles. The study introduced three failure criteria based on 5%, 10%, and 15% reductions in strain amplitude, and compared them to fatigue life predictions obtained from modal degradation. Strikingly, a reduction in resonant frequency was found to correlate strongly with crack initiation, whereas damping factor increases provided less reliable indicators. The researchers further validated their observations using SEM fracture surface analysis, which revealed both transgranular fatigue striations and rare intergranular fractures—an unusual observation at this frequency range. To interpret the $\varepsilon$–$N_f$ data, the study used Basquin, Stromeyer, and Papadopoulos equations, highlighting the limitations of classical fatigue models and offering refined regression-based alternatives. The findings position resonant frequency shift as a promising, non-intrusive crack detection parameter, enabling future testing without localized strain measurement. Palani et al. demonstrate effective cycle counting under random excitation, while Khalij et al. offer a high-resolution analysis of fatigue behaviour using advanced control and fracture diagnostics. The former emphasizes real-time fatigue damage from external dynamic input, and the latter internal structural health monitoring via resonance tracking. Their convergence lies in establishing empirical fatigue curves and predictive models that enhance the reliability of fatigue life assessment under vibratory conditions, contributing to safer design and monitoring of structural components in aerospace, automotive, and mechanical systems.

The investigation of vibration and noise behaviour in automotive brake systems has been significantly advanced through integrated numerical-experimental approaches, particularly when alternative rotor materials are considered. Two notable studies exemplify this trend, focusing on siliconized carbon composite and cast-iron rotors under dynamic loading conditions.

In the comprehensive study by Ioannidis et al. (2005), a detailed back-to-back comparison was conducted between grey cast iron and siliconized carbon composite (CMC) brake rotors using a combination of finite element complex eigenvalue analysis (CEA) and dynamometer-based noise testing. The authors simulated brake squeal, a friction-induced instability within the 0–17 kHz range, using ANSYS FE models and validated the results against experimental modal analysis (EMA). Material properties were carefully tuned: the grey cast iron had a Young's modulus of 110 GPa, whereas the lighter CMC rotor (35 GPa) achieved similar natural frequencies due to geometric matching. Crucially, the FE analysis revealed unstable modes (7439 Hz and 12485 Hz for the cast iron setup), and these aligned closely with measured squeal frequencies during J2521 dynamometer testing (7600 Hz and 11800 Hz). The study also modelled nonlinear contact mechanics using friction springs and simulated pseudo-dynamic drag braking to define realistic interface boundaries between pads and rotor. Experimental testing confirmed that cast iron systems were more prone to squeal, especially under high temperature (>150 °C) and pressure (10–20 bar) conditions. Conversely, the CMC rotor system exhibited a "quiet" performance across all test scenarios, attributed to better damping characteristics and thermal stability. The authors extended their investigation to thermoelastic instability (TEI) using the "Hotspotter" FE tool. Critical speeds for hotspot formation were an order of magnitude higher in the CMC rotor (~5500–10000 rad/s), making it significantly more resistant to thermal judder. This study demonstrated how integrating validated FE eigenvalue methods with experimental dynamometer testing can yield accurate NVH predictions and inform material selection for high-performance braking systems.

Complementing this, the earlier paper by Ioannidis et al. (2004) focused more deeply on the non-linear contact mechanics and modal sensitivity contributing to brake squeal. Using the same test facility at the University of Leeds, this research adopted a multistage FE strategy. First, nonlinear contact simulations under varied actuation pressures were conducted to estimate interface behaviour. Then, these results were used to construct a linearized eigenvalue problem incorporating frictional effects. A key contribution of this study was the sensitivity analysis of modal instability with respect to the friction coefficient, revealing that increased friction (from 0.4 to 0.6) not only raised instability magnitudes but also introduced additional unstable modes (e.g., at 9787 Hz and 10748 Hz). Interestingly, while cast iron rotors with polymer matrix composite (PMC) pads showed high squeal activity, siliconised carbon composites suppressed squeal even at extreme thermal and load conditions. Experimental validation via the J2521 matrix supported the computational predictions: squeal levels exceeded 105 dB for the cast iron systems, while the CMC rotor remained quiet under identical pressures and speeds. The strong correlation between simulation and experiment emphasized the importance of including realistic boundary conditions and material damping in FE models. Furthermore, the study's thermal judder evaluation underscored how material selection impacts TEI critical speed, noting again that the CMC disc’s high thermal conductivity and low expansion coefficient drastically improved thermal stability.

Together, these works provide a cohesive narrative on how advanced material substitution (e.g., CMC for cast iron), coupled with sophisticated simulation and testing frameworks, can dramatically reduce NVH issues in brake systems. They establish a validated, multi-physics methodology that blends structural dynamics, friction mechanics, and thermal modeling — paving the way for future design of quieter, more stable, and thermally robust braking components.

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Few research papers explores two significant experimental studies aimed at understanding the dynamic response and health assessment of welded steel structures through vibration-based damage detection and modal analysis. While both studies adopt different configurations—pipes vs. joints—they converge on the common objective of enhancing structural integrity diagnostics through dynamic measurements.

In a comprehensive structural health monitoring (SHM) investigation, Hassan et al. (2015) evaluated the dynamic behaviour of welded carbon steel (ASTM A106 Grade B) pipes using vibration-based methods. The study compared Shielded Metal Arc Welding (SMAW) and Gas Tungsten Arc Welding (GTAW) joints, integrating both static (3PB, tensile, buckling) and dynamic (Frequency Response Functions, modal damping) evaluations. Artificial cracks were introduced in the welds to simulate defects. Four modes were extracted experimentally using uniaxial accelerometers and an impact hammer, analyzed through an FFT analyzer. The damping ratio and modal frequencies were measured with and without cracks, showing consistent reductions in damping and frequency upon crack introduction—e.g., damping dropped from 8.110% to 6.569% in GTAW joints. Notably, SMAW exhibited a slightly higher damping ratio, indicating lower stiffness. The results indicated that FRF-based modal characterization is a robust technique for SHM, as vibration characteristics sensitively reflected joint integrity. This study is notable for showing how subtle differences in welding technique, crack size, and excitation frequency influence damage detection reliability, making it especially relevant for pipeline monitoring and high-temperature applications.

In a more application-specific context, Ranjan and colleagues (2019) investigated the vibrational behaviour of bolted and welded joints in steel L-angle structures using experimental modal analysis under free-free boundary conditions. Their objective was to assess how joint configuration impacts modal damping and natural frequencies. Using mild steel for fabrication, they employed accelerometers and impact testing to extract modal parameters such as mode shapes, damping ratios, and frequencies. Welded joints showed higher stiffness and lower damping compared to bolted joints. Specifically, for the first bending mode, the frequency was ~260 Hz for welded joints versus ~200 Hz for bolted ones. Similarly, damping in bolted joints was ~2.9% versus ~1.7% in welded ones. These differences were attributed to energy dissipation mechanisms inherent in bolted interfaces (e.g., micro-slips). This study emphasizes that welded joints, despite offering stiffness advantages, are less capable of energy dissipation, which could affect vibration isolation in mechanical structures. Furthermore, mode shape visualizations demonstrated that joint locations acted as strain concentration zones, reinforcing the critical need for joint-specific vibrational design. This work directly supports structural engineers in choosing between joint types based on the desired trade-off between rigidity and damping. Together, these studies underscore the complementary roles of material configuration, joining methods, and crack presence in altering the dynamic response of steel structures. Hassan et al. validate vibration-based SHM in complex pipe systems, while Ranjan et al. provide insights into joint design optimization from a dynamic performance perspective. Both contribute to a growing body of research where vibration metrics act as diagnostic fingerprints, offering engineers valuable tools for both preventive maintenance and design refinement.

The research carried out by few researchers' incudes two distinct experimental investigations where one on high-frequency thermally induced vibration in steel blades and the other on ultrasonic vibration effects on wear mechanisms in carbon steel. Despite their differing motivations and frequencies, both studies converge in revealing how dynamic excitation alters structural behaviour and surface integrity.

Sathish Kumar et al. (2016) studied the dynamic response of mild steel blades exposed to thermal loads, simulating conditions experienced in turbines and exhaust systems. The objective was to analyse frequency and amplitude shifts under varying temperatures. Using an FFT analyser with accelerometers, they recorded the blade's response as temperatures rose from 0°C to 700°C in 100°C increments. The analysis revealed a consistent decrease in natural frequencies with rising temperature, attributed to material softening and changes in stiffness. For example, the fundamental natural frequency declined from ~300 Hz at 0°C to ~260 Hz at 700°C. Additionally, they noted significant increases in amplitude, indicating higher energy absorption and possible onset of instability at elevated thermal states. This study emphasizes the need for thermal-aware design in dynamic steel components. The use of FFT and experimental modal analysis (EMA) helped capture the real-time evolution of vibrational modes, offering a pathway for integrating temperature-dependent vibration monitoring in structural health diagnostics.

In contrast, the earlier but equally impactful study by Goto et al. (1984) focused on the wear behaviour of carbon steel under ultrasonic vibration. Here, instead of structural deformation, the primary concern was the material degradation mechanism. Through a pin-on-disk wear-testing setup operating at 22 kHz and amplitudes up to 12 μm, the authors systematically investigated how vibration altered the adhesive wear regime. The carbon steel specimens, subjected to static loads and sliding velocities, exhibited a marked reduction in wear rate with increasing vibration amplitude. Analytical modelling combined with experimental findings suggested that reduced contact time per vibration cycle, along with increased oxygen adsorption, were the primary mechanisms reducing wear. Particularly, it was observed that ultrasonic-induced dynamic separation (or "jumping") limited real surface interaction, thereby minimizing junction formation and wear debris generation. The study developed a novel wear rate equation incorporating dynamic contact mechanics and adsorption kinetics, linking activation energy of oxygen adsorption to vibration-induced surface activation. Notably, while work hardening did occur, its influence on wear rate was minimal in contrast to oxygen adsorption. This work highlights how ultrasonic excitation not only modifies mechanical response but fundamentally alters tribological processes. Together, these papers illustrate a broader spectrum of vibration-induced phenomena in steel structures — from temperature-induced frequency shifts compromising mechanical stability (Sathish Kumar et al.) to micro-scale contact modulation improving wear performance (Goto et al.). Both underscore the versatility of vibration-based diagnostics and interventions in enhancing structural longevity and functionality under extreme operational conditions.

Few scientists focused on substantial insights, how mechanical vibrations influence the mechanical and microstructural properties of stainless – steel specimens, particularly in the context of welding processes. Though both papers deal with stainless steel, they differ in methodological emphasis — vibro-welding analysis (Sakthivel & Sivakumar, 2014) versus modal frequency response testing (Swamy et al., 2013).

Swamy et al. (2013) explored the free and forced vibration behaviour of stainless steel (SS304) cantilever beams by focusing on the modal frequency and dynamic amplification factors. The study utilized a modal analysis test setup with accelerometers and an impact hammer to capture time-domain responses under various boundary conditions. The findings highlighted how natural frequency and mode shapes changed with support constraints. The analytical results using ANSYS and MATLAB were validated by experimental data, and discrepancies remained within a 3%–5% error margin. Their work effectively demonstrated that geometric constraints and damping properties significantly influence vibrational characteristics. The primary novelty lies in the quantitative correlation between experimental modal analysis and finite element simulation, offering engineers a reliable way to predict vibrational behaviour in structural applications involving stainless steel.

In contrast, Sakthivel and Sivakumar (2014) focused on how vibration-assisted welding alters the mechanical strength and microstructure of AISI 316 stainless steel**.** The authors applied mechanical vibration (using a motor-induced vibratory fixture at speeds of 800–1050 RPM) during both TIG and arc welding processes performed in the vertical 3G position. Through a battery of mechanical tests—Rockwell hardness, Charpy and Izod impact, tensile strength, and microstructure analysis—they demonstrated that vibration improved mechanical performance significantly. For instance, Rockwell hardness rose from an average of 49 (no vibration) to 66.6 (1050 RPM) in TIG-welded samples. The ultimate tensile strength (UTS) also increased from 494.6 MPa to 622.5 MPa, while elongation improved from 4% to 12.5%, reflecting enhanced ductility. Microstructure analysis revealed grain refinement and complete fusion in vibrated samples. The mechanisms attributed to these improvements included grain homogenization, stress relaxation, and enhanced solidification dynamics due to vibrational energy. Notably, the study confirms the utility of vibration as a cost-effective alternative to post-weld treatments for improving weld quality. Together, these studies reinforce the transformative potential of vibration-based interventions in enhancing the structural reliability and mechanical performance of stainless – steel components. While Swamy et al. provide insights on dynamic behaviour and frequency analysis, Sakthivel and Sivakumar emphasize material property enhancement during welding, underlining complementary dimensions of vibration application.

It has been observed that, few authors have focused on the application of finite element analysis (FEA) for vibration studies of engine components — specifically crankshafts and cylinder liners — under different excitation sources and boundary conditions. The methodologies reflect growing interest in using simulation tools like ANSYS to predict structural response without invasive testing. Chavhan and Soman (2017) conducted a numerical investigation into the vibrational behaviour of a diesel engine crankshaft, treating it as a fixed beam undergoing transverse harmonic excitation. Their analysis aimed to understand how engine speed and load variations influence the dynamic response of crankshafts made of EN8 steel. The study used ANSYS 14.5, with the crankshaft modelled as a beam subjected to moment loads and torsional constraints. The authors performed both modal and harmonic analyses, observing that maximum deformation occurred at the crank-pin centre, confirming the stress concentration location. Frequency response curves indicated resonance near 155 Hz, aligning with the natural frequency range of the system. The research established the need for precise identification of operational frequencies to avoid resonance during running conditions. Furthermore, they compared simulated values with analytical solutions derived from classical beam theory, finding good correlation within 5%. This not only validated their modelling approach but reinforced the importance of FEA in preliminary design refinement to enhance fatigue life and reliability of engine shafts. Complementing this, Bhansali and Shirgire (2014) focused on a diesel engine cylinder liner, analysing its vibrational response under combustion gas forces and varying liner thicknesses. Using ANSYS 10, they modelled the liner as both a 2D beam and a

3D cylinder, investigating deformation under combustion pressures ranging from 45 to 75 bar. Materials analysed included FG150, FG260, and FG400 grades of grey cast iron, comparing their deflection responses in both Y and Z directions. The harmonic analysis revealed that FG400 exhibited the least deflection, making it more suitable for high-pressure conditions. Additionally, the authors explored the influence of increasing liner thickness by 1 mm, which significantly reduced amplitude of vibration, confirming that design modifications could mitigate vibrational hazards. The study emphasized the impact of material grade and geometric reinforcement in dynamic environments. They also captured nodal deflection patterns and plotted displacement vs. frequency curves to visualize dynamic response. Unlike earlier works focused on piston slap, this study uniquely integrated combustion-induced harmonic loads in a structural simulation context, offering design-centric insights for liner stability.

The research community has investigated the intricate effects of mechanical vibration and heat treatment on the mechanical properties and structural integrity of mild steel weldments. While both papers use mild steel and investigate vibratory welding, their experimental scope and conclusions differ in methodology, vibratory regimes, and the degree of post-weld thermal processing. Ojo et al. (2019) presented a systematic analysis of how varying vibration frequencies during welding and post-weld annealing affect the hardness and impact toughness of butt-welded low-carbon steel joints. They employed three vibrational frequencies—0 Hz (no vibration), 7.96 Hz, and 14.32 Hz—combined with five annealing temperatures ranging from 350°C to 750°C. The mechanical tests included Rockwell hardness and notch-bar impact testing, carried out across the weld zone, heat-affected zone (HAZ), and parent metal. Their data showed that the weld zone consistently displayed the highest hardness, with values reaching up to 41.8 HRC under 14.32 Hz vibration and 350°C annealing. However, the impact toughness generally decreased with vibration, particularly at higher frequencies, indicating a trade-off between strength and ductility. Notably, annealing at moderate temperatures (450°C–650°C) helped balance this trade-off, improving impact performance while maintaining hardness. The authors attributed the improved mechanical response to grain refinement and residual stress relaxation from vibration, while the deterioration in impact toughness at high frequency was linked to microstructural brittleness and possible defect formation. This study is valuable for its nuanced portrayal of synergistic effects between vibrational and thermal treatments on steel joints. In parallel, Manoj and Padmanaban (2014) explored a similar vibratory welding context, focusing on butt-welded mild steel plates subjected to varying frequencies of 0 Hz, 4.5 Hz, 7.96 Hz, and 14.32 Hz. Their work emphasized mechanical property enhancement without incorporating post-weld heat treatments. Through comprehensive testing—Brinell hardness, Charpy impact, and tensile strength—they concluded that moderate vibration (around 7.96 Hz) led to a significant increase in both strength and ductility, achieving tensile strength values as high as 602 MPa and an elongation of 15%. Microstructural analysis revealed fine-grained ferrite-pearlite structures in vibrated samples compared to coarse grains in non-vibrated ones. Unlike Ojo et al., this study observed that impact toughness and hardness could both be enhanced with the correct vibrational input. However, at the highest frequency (14.32 Hz), slight brittleness was reported, aligning with the observations from Ojo et al. The absence of annealing makes this study particularly relevant for real-time fabrication environments, where time or equipment constraints may not allow post-processing.

Few authors dealt with the experimental vibration analysis during milling operations of steel-based materials, focusing on the relationship between cutting conditions, tool geometry, and the resulting surface integrity. They underscore how chatter amplitude and vibration characteristics can significantly influence surface finish, process stability, and machining accuracy. The study by Kumar et al. (2015) investigates the vibrational behaviour of mild steel workpieces during end milling under dry conditions. The researchers applied Fast Fourier Transform (FFT) to identify frequencies and amplitude shifts during the milling process at various speeds (200, 400, and 600 rpm). They measured amplitude variations along X, Y, and Z axes using a three-axis accelerometer and captured dominant natural frequencies ranging from 2500 Hz to 6000 Hz. The amplitude and frequency peaks increased with speed, revealing the onset of resonance and chatter at higher spindle speeds, particularly in the Y and Z axes. Surface roughness measurements further demonstrated that excessive vibration led to irregular tool paths and poor finish. Notably, the study observed that the direction of maximum vibration did not always align with the feed direction, indicating the complex interplay of machine-tool-workpiece dynamics. The research strongly supports using vibration signals as a real-time indicator of machining quality. The authors recommend optimizing speed and feed to avoid dynamic instability and advocate for future integration of active damping mechanisms or process monitoring systems in precision machining. Complementarily, Amin et al. (2010) focused on the effect of chatter amplitude on surface roughness during the end milling of medium carbon steel (S45C) using two different cutter diameters: 16 mm and 20 mm. Their experimental setup involved recording vibration signals using an online monitoring system, while surface roughness (Ra) was measured using a SURFTEST SV-500 device. The chatter frequency spectra were analysed using FFT to generate stability lobe diagrams, which helped identify the critical cutting speed ranges prone to chatter—between 150–225 m/min for 16 mm tools and 200–250 m/min for 20 mm tools. The maximum Ra observed was 2.87 µm at 150 m/min (for the smaller cutter), confirming that higher chatter amplitudes correspond to worse surface finish. Interestingly, the larger diameter tool showed greater stability and lower roughness (Ra = 1.49 µm at the same speed), suggesting that tool stiffness and cutter geometry play crucial roles in chatter suppression. The paper also highlighted how increasing speed leads to a non-linear behaviour in chatter amplitude due to resonance interactions with system modes. The authors concluded that tool design and cutting condition optimization must go hand-in-hand to control vibration and enhance machined surface quality, especially in medium carbon steels susceptible to thermal-mechanical instability.

After going through the existing literature, it is seen that few studies covered finite element analysis (FEA) for assessing the modal and harmonic vibration responses of mechanical structures. In the work of Mahapatra et al. (2021), the authors undertook a numerical simulation of a mild steel structure subjected to a transient point load using ANSYS Workbench. They created a CAD model with specified geometric constraints and subjected it to a time-varying point force of 1000 N. Modal analysis revealed five natural frequencies ranging from 142.9 Hz to 2050.2 Hz, with accompanying mode shapes displaying vertical, torsional, and lateral deflections. Subsequently, harmonic response analysis was conducted across a frequency range of 0–3000 Hz, showing resonance peaks at frequencies matching natural modes. Notably, the structure experienced maximum deformation near the mid-span, where dynamic amplification was highest. The authors emphasized the importance of capturing both modal and harmonic responses to ensure design safety, especially in components exposed to repeated or fluctuating forces. This study's contribution lies in its clear illustration of how simple load cases can be used to extract crucial insights about resonance-prone regions and the behaviour of structures under forced vibration. It provides a foundation for the use of FEA in early-stage mechanical design validation. On the other hand, Ashwani Kumar et al. (2014) explored the free vibration behaviour of a transmission gearbox casing made from grey cast iron, structural steel, aluminium alloy, and magnesium alloy. Their primary objective was to examine how the mechanical properties of materials—such as density, Young's modulus, and damping characteristics—influence natural frequencies and mode shapes. Using ANSYS 14.5, they conducted a modal analysis for the first 20 natural modes under a fixed–fixed boundary condition, simulating a real-world bolted mounting. The study revealed significant frequency differences: grey cast iron (1002–2954 Hz), structural steel (1306–3879 Hz), aluminium alloy (1291–3829 Hz), and magnesium alloy (1273–3784 Hz). Mode shapes included torsional and axial bending vibrations, with higher modes producing more pronounced deformation. Interestingly, materials with lower density (Al and Mg alloys) showed lower stiffness, causing higher deformation in some modes, while structural steel provided the most rigid behaviour, making it suitable for heavy machinery casings. The simulation results were validated by comparing frequency ranges with experimental literature. This comprehensive study highlighted that material selection critically impacts the vibrational signature of structural components, and FEA can reliably predict such effects.

The research performed by few authors, has covered the experimental investigations focused on understanding the vibrational behaviour of different metallic materials — aluminium alloy (Al6061-T6) and various grades of cast iron — under dynamic excitation. These studies approach vibration response through modal parameters such as natural frequencies, damping ratios, and mode shapes, but with distinct objectives: one explores boundary conditions, while the other links vibration to material fatigue life. Kantharaju et al. (2018) examined the effects of different boundary conditions on the modal and harmonic response of an aluminium alloy beam (Al6061-T6). The study involved a systematic experimental modal analysis using an impact hammer and FFT analyser, along with LMS Test Lab software for data acquisition. The beam was tested under four types of end conditions: free-free, simply supported, clamped-free (cantilever), and clamped-clamped. The authors extracted key parameters like natural frequencies, damping ratios, and mode shapes. Their findings showed that the clamped-clamped condition resulted in the highest natural frequencies and damping, due to increased stiffness and reduced energy dissipation. In contrast, the free-free configuration had the lowest modal values and more prominent vibration amplitudes, making it more prone to resonance. The study clearly emphasized how support constraints directly affect dynamic stiffness and energy dissipation, a crucial insight for structural engineers designing lightweight and vibration-sensitive components. Additionally, harmonic analysis revealed amplitude peaks corresponding to the beam's natural frequencies, confirming resonance. This paper offers valuable experimental data and practical understanding of how boundary choices can influence real-world vibrational responses in aerospace and structural applications using aluminium. On the other hand, Damir et al. (2007) explored a more material-centric perspective by correlating vibration damping characteristics to microstructure and fatigue life across three types of cast iron—grey cast iron, ductile cast iron, and austempered ductile iron (ADI). Their study used experimental modal analysis to determine the natural frequencies and damping ratios of small rectangular specimens under identical conditions. Tools included an impact hammer, accelerometer, and Brüel & Kjær Pulse system for frequency response function (FRF) analysis. Their modal results showed that ADI exhibited the highest damping ratios, followed by ductile and then grey cast iron. These differences were attributed to the graphite morphology and matrix phase differences within the materials. To bridge the vibration data with fatigue performance, they also performed rotating bending fatigue tests and observed that materials with higher damping ratios generally had longer fatigue lives. Moreover, microstructural examination revealed that damping performance was influenced not just by material stiffness but also by the energy dissipation mechanisms embedded within the microstructure—e.g., nodular vs. flake graphite. A key contribution of the study was the establishment of a semi-empirical model that correlated modal damping ratios with fatigue strength, offering a novel approach to predict fatigue life using non-destructive vibration data. This work is particularly important for component designers seeking early-stage fatigue predictions using vibrational signatures.

In the work by Gandhi et al. (2019), a finite element model was developed to study the nonlinear free and forced vibration of a frictionally damped beam. The authors modelled the beam as a clamped – clamped system, incorporating Coulomb friction at specific contact interfaces, and applied the Galerkin method to derive a reduced-order model. Their analysis covered both free vibration decay and forced harmonic excitation, using MATLAB to numerically simulate the system. One important observation was that the friction force introduced a strong nonlinearity, leading to phenomena such as frequency softening and amplitude modulation. In the forced response case, the amplitude decreased as excitation frequency increased, and jump phenomena were observed, typical of nonlinear systems. Additionally, the system showed multiple stable and unstable equilibrium points, and the hysteresis loop area increased with friction coefficient, reflecting higher energy dissipation. This study is significant for structural applications involving repeated contacts or joints, such as bolted or riveted assemblies, where frictional energy loss can dampen vibrations but also introduce complexities in dynamic behaviour. Complementing this, the study by Paliwal et al. (2005) dives into the mechanisms of brake squeal in disc–pad assemblies, applying a nonlinear stick–slip friction model that includes coupling stiffness from tribo-layers at the contact interface. Using a two-degree-of-freedom lumped parameter model, they simulated dynamic behaviour under various mass, damping, and friction scenarios. The coupling stiffness was modelled as a combination of modal stiffness of the pad and layer stiffness of the friction film formed during braking. Through phase space analysis, the authors observed that increasing coupling stiffness could either stabilize or destabilize the system, depending on the damping distribution. The model revealed that nonlinear friction characteristics (velocity-dependent) dramatically affected the limit cycles—with larger stiffness values leading to system instability unless adequately damped. The work clearly showed that friction-induced instabilities are governed not only by the friction coefficient but also by dynamic variations in contact stiffness, which arise from material deposition and wear. The insights are valuable in automotive brake design, where noise and vibration must be controlled without compromising braking performance. Together, these papers highlight how friction and nonlinear stiffness mechanisms shape the vibrational response of systems. Gandhi et al. emphasize how Coulomb damping alters structural resonance and energy dissipation, while Paliwal et al. underscore the complex interplay between friction layers and coupling stiffness in brake systems. Both provide deep insights for the predictive modeling of vibration behaviour in real-world mechanical and automotive assemblies.

In the study by Kowsalya and Prabhakaran (2022) [vib-new-39], the authors performed a comprehensive experimental vibration analysis of a mild steel cantilever beam to explore its dynamic characteristics. The beam was designed with a length of 500 mm and cross-sectional dimensions of 30 mm × 10 mm. Strain gauges were attached to capture strain data at various positions, which were then used to determine mode shapes and frequency responses. A modal analysis was conducted using a fast Fourier transform (FFT) based spectrum analyzer, with excitations introduced through hammer impacts. Notably, the natural frequency of the beam was found to be in the range of 96 Hz, and the strain variation provided insight into how displacement modes shifted with higher harmonics. The testing revealed that the first mode was predominantly bending-dominated while higher modes exhibited increased torsional coupling. The authors highlighted how even modest changes in geometry or loading conditions could significantly affect vibration behaviour, especially in slender metallic beams. This paper reinforces the importance of accurate strain data acquisition for dynamic mode interpretation, particularly in experimental setups involving simple support conditions and metallic materials like mild steel.

In contrast, the research by Sharafi et al. (2021) [vib-new-40] offered a large-scale, structural-level vibration study on a volumetric steel modular frame, exploring both ambient and free vibration responses. A full-scale prefabricated steel module was tested in a lab setting using six accelerometers placed at strategic roof-level points. The specimen, designed for a multistory building, featured structural components including SHS columns (200 × 200 × 6 mm), UB floor and ceiling beams, and cold-formed steel joists. The study employed various Operational Modal Analysis (OMA) techniques, including FFT, Enhanced Frequency Domain Decomposition (EFDD), and Stochastic Subspace Identification (SSI), to extract modal properties such as natural frequencies and damping ratios. Their experimental tests involved 12 distinct hammer impacts to stimulate multiple vibration modes, while numerical finite element models (macro and micro) were used for validation. The first few natural frequencies were in the range of 6.4–8.2 Hz (for the L-direction), with additional peaks identified up to 124 Hz. The damping ratios ranged from 4.6% for the first mode to about 0.6% for higher modes. Notably, the results emphasized that pure ambient vibrations were insufficient alone for reliable identification, while forced vibrations yielded much more discernible modal patterns. Together, these studies reflect the wide spectrum of vibration analysis approaches—from component-level experimental strain gauge methods (as in mild steel beams) to full-structure OMA using advanced sensor layouts and modelling. Despite their scale difference, both emphasize the role of excitation type, sensor positioning, and algorithmic processing in accurately identifying vibrational behaviours of steel-based structures.

In the work by Choudhary et al. (2020), the authors investigated the dynamic behaviour of steel beams connected through friction joints using bolts. The central aim was to understand how preload torque applied to bolts influences the damping and stiffness characteristics of the beam assembly. A test rig comprising mild steel beams was fabricated, with bolts placed at different intervals and torqued at varying levels. Using an impact hammer and accelerometers, they conducted experimental modal testing and evaluated the first few natural frequencies and damping ratios under different torque levels. The results clearly revealed that increasing torque improved the stiffness of the bolted joints, which in turn elevated the natural frequencies and reduced damping. This implies that tightly connected joints behave more rigidly, reducing vibrational energy dissipation. On the other hand, beams with lower torque showed more damping due to micro-slip at the interface, absorbing vibrational energy. The authors emphasized the importance of correctly tuning bolt preload in practical structures to achieve the desired dynamic performance, such as in bridges, cranes, or machine frames. Their research provided crucial insights into how joint stiffness and friction damping interact, affecting vibration response in real-life assemblies. In contrast, Sharma (2019) presented a thorough theoretical, experimental, and numerical modal analysis of a single beam under two boundary conditions—free-free and simply supported. The aim was to compare the results across all three methods to validate each other. For theoretical analysis, classic Euler–Bernoulli beam theory was applied, while finite element analysis (FEA) was performed using ANSYS Workbench 14.5**.** Experimental modal analysis (EMA) was conducted using an impact hammer and Polytec Laser Vibrometer (NLV-2500). For the simply supported condition, one end was hinged and the other on rollers, whereas the free-free beam was suspended using fine wires. The time-domain response from the vibrometer was converted to frequency-domain using FFT in MATLAB. The first three natural frequencies were then extracted. The results demonstrated good agreement across theoretical, numerical, and experimental methods, with only minor discrepancies attributed to real-world imperfections such as material nonlinearity, manufacturing tolerances, and sensor resolution. For instance, the first mode for a simply supported beam was experimentally found at 12.21 Hz versus 10.61 Hz theoretically. Sharma noted that higher-order modes were not easily excitable with the impact hammer, and recommended the use of sine sweep methods for such cases. This paper stands out for its integrative validation approach, offering a complete methodology for engineers seeking reliable modal parameters across different analysis platforms. Together, these studies underscore two critical points in structural dynamics: (1) how boundary or contact interfaces, such as bolted joints or fixed supports, significantly impact modal parameters; and (2) the value of multi-method validation (theoretical, numerical, experimental) in achieving reliable dynamic characterizations. These insights are particularly applicable for structures where accurate vibrational behaviour is vital for longevity, stability, and performance.

In the domain of structural vibration analysis, the works by Memory et al. (1995) and Siddika et al. (2019) provide valuable insights, each approaching the problem with different materials, methodologies, and applications, yet offering complementary lessons in understanding dynamic behaviour. The paper by Memory et al. focuses on free vibration analysis of bridge superstructures, emphasizing how simplified static approaches in bridge design often fall short when dynamic effects are considered. Their work critically evaluates traditional empirical formulas and beam analogies, suggesting that while these models yield decent accuracy for simple, straight, and non-skewed bridges, they fail to capture real behaviour in skewed, curved, or continuous bridges. They propose a hybrid approach using the Rayleigh energy method applied to grillage models, achieving estimations within 10% accuracy. Particularly compelling is their insistence on using the dynamic modulus of elasticity instead of the static one—an important correction since using Es underestimates frequencies and can lead to unsafe bridge designs. The authors validate their methodology using the Six Mile Creek Bridge in Australia, a composite steel-concrete bridge. Their analysis shows that while simple beam analogies produce some underestimation, more complex finite-element eigenvalue analyses incorporating transverse and torsional modes yield a clearer picture of the bridge's behaviour. Notably, the eigenvalue and Rayleigh-based grillage analyses offered fundamental frequency values (around 9.95–10.40 Hz) closely matching field-measured data, strengthening the credibility of the proposed methods. In contrast, Siddika et al. explore the free vibration behaviour of mild steel moment-resisting framed structures subjected to uniaxial base excitation. Their study is more experimental in nature, combining shaking table tests with ANSYS-based numerical simulations to understand the influence of stiffness, mass, and height on natural frequencies. Four structural models were tested, with variations in wire diameter, number of storeys (8 vs 10), and the presence or absence of slabs (mass). The paper reinforces the classical understanding that an increase in mass or height leads to a decrease in natural frequency, while increased stiffness has the opposite effect. For instance, the 10-storey structure with slab (Model-2) had the lowest vibration frequency (around 2.87–3.10 Hz), whereas the lighter 8-storey model without slab (Model-3) had a higher frequency (around 3.10–3.40 Hz). The experimental results were in reasonable agreement with ANSYS modal analysis, although simulation-based frequencies were slightly higher—an expected outcome due to idealized boundary conditions in modelling. Importantly, Siddika et al. showed that repeated shaking led to degradation in stiffness and, consequently, reduced frequencies—an observation relevant to seismic resilience and fatigue assessment in real-world structures. Connecting both studies, it becomes clear that vibration characteristics are sensitive to structural geometry, material behaviour (static vs dynamic modulus), and boundary conditions. While Memory et al. stress the inadequacy of oversimplified models for bridges and advocate refined eigenvalue analyses, Siddika et al. illustrate how mass-stiffness dynamics play out in steel frames, validating their findings with both physical and numerical methods. Together, these papers highlight that vibration analysis demands a careful balance between model simplicity for practical use and accuracy for safety and performance, especially when structural responses are influenced by both longitudinal and transverse dynamic modes. The study by Tiwari et al. (2022) offers a detailed numerical investigation into the vibrational behaviour of isotropic rectangular plates with circular cut-outs, which are commonly found in aerospace, automotive, and mechanical components. The main goal of this research was to analyze how geometric parameters such as the cut-out radius, aspect ratio, and thickness of the plate affect the natural frequencies and mode shapes of the structure.

Using ANSYS Workbench, the researchers created a finite element model of a simply supported rectangular plate, assigning it isotropic material properties typical of structural steel. They performed modal analysis across a range of scenarios by varying one parameter at a time — such as increasing the radius of the circular cut-out or changing the aspect ratio of the plate. A key finding was that as the cut-out radius increased, the natural frequencies decreased significantly. This is intuitive because the presence of a cut-out reduces the stiffness and mass in a non-uniform way, making the structure more flexible and less resistant to vibration. Similarly, increasing the plate aspect ratio (length-to-width) or decreasing thickness also led to a drop in fundamental frequencies. Mode shapes were also closely examined. For plates with larger cut-outs, higher deformation was observed around the cut-out boundary, especially for the first and second modes. This localized behaviour is important because such regions are more prone to fatigue or failure under dynamic loading. The study effectively demonstrated that even a symmetric cut-out in a plate causes asymmetry in vibration patterns, affecting both performance and durability. One of the strong points of this work lies in its systematic parametric analysis, which makes it highly relevant for design engineers who deal with components like machine covers, fuselage panels, or electronic enclosures where weight reduction is achieved through cut-outs. The researchers conclude that designers must carefully balance weight-saving strategies with dynamic integrity, especially when components are exposed to cyclic or vibrational loads. Overall, this paper contributes valuable insights to vibration-based structural design, and its use of commercial FEA tools ensures that the findings can be directly implemented into industry workflows.

## Conclusion

This review paper has provided an overview of how variations in the constituent elements of metal beams affect their vibration performance. From the analysis of existing studies, it is clear that the type and number of elements play a significant role in determining the vibration behaviour of metals. Changes in elements like carbon, nickel, and chromium can alter the stiffness, damping capacity, and natural frequencies of metal beams, which are important for their stability under vibration. Vibrations during or after welding can lead to defects, reduced joint strength, and other issues that weaken the structural performance over time. This shows that both the material composition and fabrication process must be carefully controlled to ensure reliable vibration resistance.

It was observed that high temperatures cause changes in grain structure, phase transformations, and coarsening of precipitates, which in turn reduce the ability of metals to handle vibrations effectively. This is especially important in industries where metals are used in high-heat environments, such as power plants and aerospace. Future studies should focus on integrated approaches that consider these factors together, using advanced experimental methods and modelling tools. The insights presented in this review can help engineers and researchers make informed choices when selecting materials and designing metal structures to perform reliably under dynamic and harsh conditions.

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