Jurnal Kejuruteraan 38(7) 2026: 3271-3286
https://doi.org/10.17576/jkukm-2026-38(7)-09

Finite Element Method for Sustainable Structural Integrity of Multi-bolted Flanges: A Review of Optimized Design and Green Maintenance Strategies

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Received 25 January 2026, Received in revised form 9 July 2026
Accepted 9 August 2026, Available online 30 October 2026

ABSTRACT

Multi-bolted flange (MBF) connections are essential components of piping systems, pressure vessels, offshore structures, renewable energy infrastructure, and process plants. However, their long-term reliability is often affected by complex mechanical loading, thermal cycling, gasket degradation, corrosion, bolt preload loss, and uneven force distributions. These technical challenges can lead to leakage, fatigue failure, unplanned shutdowns, repeated component replacement, and increased material waste. This review examines the role of the Finite Element Method (FEM) in improving the sustainable structural integrity of MBF systems through optimised design and green maintenance strategies. Recent studies have been synthesised to show how FEM supports stress distribution analysis, bolt preload evaluation, gasket contact-pressure prediction, fatigue life assessment, leakage prevention, corrosion risk evaluation, and structural health monitoring. Particular attention is given to how FEM-driven modelling can reduce overdesign, improve sealing performance, extend service life, and support predictive maintenance by identifying critical failure mechanisms before field failure. This review also highlights the importance of bolt modelling conditions, including preload definition, contact interaction, gasket compressibility, frictional behaviour, mesh refinement, and service-induced load combinations. Although FEM has significantly advanced the understanding of MBF performance, important research gaps remain in the integration of FEM with self-healing materials, real-time adaptive control, sensor-based monitoring, machine learning validation, and digital twin maintenance frameworks. Overall, this review demonstrates that FEM provides a practical pathway for achieving safer, more reliable, and more resource-efficient MBF systems while supporting sustainable engineering and environmental protection.

Keywords: Structural Health Monitoring (SHM); sustainable construction engineering; green technology, fatigue life prediction; leakage prevention

INTRODUCTION

In an era defined by global imperatives for sustainable construction and green technology, industrial infrastructure faces the dual challenge of ensuring operational reliability while minimising environmental and economic expenses. Multi-bolted flange (MBF) connections, as shown schematically in Figure 1, consist of paired flanges, multiple circumferential bolts, and a gasketed sealing interface, and are fundamental to piping systems, pressure vessels, and renewable energy installations (Grzejda 2019a; Grzejda & Parus 2021).

Exposure to complex mechanical loads, thermal cycling, and corrosive environments often leads to failures such as leakage, fatigue, and bolt loosening, which disrupt sustainable development by causing unplanned downtime, excessive material waste, and potential environmental contamination. Traditional maintenance strategies that rely on reactive interventions and resource-intensive inspections are poorly aligned with the principles of eco-efficient engineering, underscoring the need for data-driven sustainable solutions.

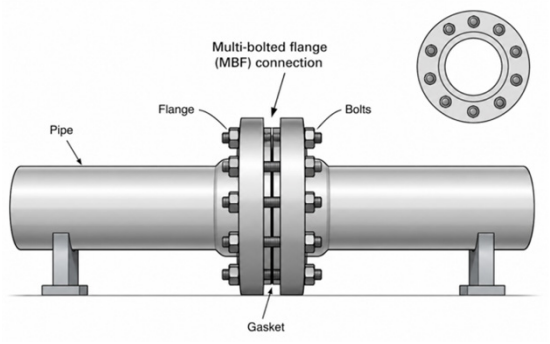


FIGURE 1. Schematic representation of a multi-bolted flange (MBF) connection in an industrial piping system, showing the main components, including the pipe, flange, bolts, and gasket.

The Finite Element Method (FEM) has emerged as a pivotal tool for addressing these challenges by enabling precise predictive analyses of MBF behaviour. By simulating stress distributions, deformation dynamics, and contact mechanics, FEM facilitates proactive strategies that enhance structural integrity while advancing the sustainability goals of the design.

This broader sustainability-oriented role of FEA is also reflected in recent composite shell studies, where numerical modelling has been used to evaluate the deformation, stress, strain, buckling, bending, torsional, and hydrostatic-pressure responses of lightweight composite cylindrical shell structures, thereby supporting material-efficient and structurally reliable design for marine and pressure-resisting applications (Huang et al. 2026; Matos et al. 2023; Shen & Pan 2021).

For instance, FEM-driven optimised designs reduce material overengineering and energy consumption by identifying critical stress concentrations, thereby minimising waste and promoting resource efficiency. In the maintenance context, FEM supports the predictive monitoring of bolt preload instability and fatigue progression, reducing the need for unnecessary component replacements and lowering the carbon footprint associated with reactive maintenance (X. Lu et al. 2025; Sanvito et al. 2024).

Additionally, in corrosive environments, FEM models help mitigate leakage risks by optimising gasket designs and material selection, thereby directly contributing to environmental safety and ecological balance of the environment.

This review synthesises recent FEM advancements that drive sustainable engineering in the context of MBF connections. It explores how FEM enhances fatigue life prediction under cyclic loads to extend component lifespans, thereby reducing material waste and supporting circular-economy principles.

It also examines thermal-mechanical modelling for leakage prevention in chemical and water systems, which is a critical aspect of safeguarding ecosystems from hazardous releases. Finally, this review highlights the integration of FEM with real-time monitoring to enable strategic low-waste maintenance practices that align with global objectives for resilient and economically viable infrastructure.

By bridging technical innovation with sustainability imperatives, this study demonstrates how FEM can foster eco-friendly industrial systems, contributing to the global agenda for sustainable construction and technology while addressing the journal's focus on green engineering, optimised design, and strategic environmental stewardship (Bhosle et al. 2025; Delo et al. 2025).

COMMON DEFECTS IN MULTI-BOLTED FLANGES AND THEIR SUSTAINABLE ENGINEERING IMPLICATIONS

MBF connections are susceptible to a range of defects arising from mechanical, thermal, and environmental interactions, each of which poses a risk to operational safety and sustainability. Below, we analyse these defects through the lens of resource efficiency, environmental protection, and green maintenance, highlighting how FEM-driven solutions address both technical and sustainability challenges.

UNEVEN LOAD DISTRIBUTION: IMPACT ON STRUCTURAL EFFICIENCY AND RESOURCE WASTE

The uneven load distribution in MBF connections stems from geometric imperfections (e.g. flatness divergence), asymmetric loading, or misaligned supports, leading to stress concentrations that degrade the structural reliability. Lu et al. (2021) studied pipelines transporting water-containing hydrofluoric acid and found that misaligned supports induced bending moments exceeding the allowable working pressure of the flange, causing leaks. The FEM analysis showed that positioning the flanges at zero-bending moment points reduced the leakage risk by 40%, illustrating the role of support layout optimisation in preventing environmental hazards.

Okorn et al. (2021) investigated dynamic bolt loads in flange joints and observed that additional bending loads increased linearly until joint separation, after which load escalation accelerated, reducing bolt fatigue life. Their work highlighted high-strength washers as a mitigation strategy, shifting the critical fatigue point from the thread roots to the bolt shank-head transition, a modification that

extended the fatigue life by 25%, reduced the replacement frequency, and aligned with the principles of the circular economy.

Ji et al. (2023) used FEM to quantify the impact of initial flatness divergence on stress distributions in offshore wind turbines, revealing that 0.5 mm flatness deviations increased stress concentrations by 30% in tower flanges. This finding underscores the need for geometric tolerance control in renewable energy infrastructure to avoid premature failure and associated material waste. Grzejda et al. (2021) further showed that asymmetric bolt positioning in multi-bolted connections caused preload variations of up to 18%, necessitating FEM-based load-sharing analyses to optimise bolt layouts and reduce engineering.

The connection between technical defects and material waste in MBF systems can be understood through repeated repair, replacement, and overdesign cycles triggered by unresolved joint problems. Uneven bolt preload, flange rotation, gasket stress loss, corrosion attack, and fatigue damage not only reduce mechanical reliability, but also increase the consumption of bolts, gaskets, flange components, sealing materials, inspection resources, and maintenance labour.

For example, a non-uniform load distribution may accelerate bolt fatigue and require premature bolt replacement, whereas insufficient gasket contact pressure may lead to leakage, gasket replacement, shutdown, cleaning, and possible disposal of contaminated materials. Similarly, corrosion degradation can require flange resurfacing, protective coating, or component replacement, whereas conservative design responses may increase the flange thickness and bolt size beyond what is structurally necessary.

Therefore, technical defects in MBF connections are directly linked to material waste because they shorten the service life, increase the corrective maintenance frequency, promote unnecessary replacement, and encourage resource-intensive overdesign. FEM-driven assessment helps reduce waste by identifying the dominant defect mechanism, optimising the load distribution, improving the sealing pressure, and supporting targeted maintenance rather than broad component replacement.

LEAKAGE MECHANISMS AND DETECTION: ENVIRONMENTAL RISKS AND ECO-EFFICIENT MITIGATION

Leakage in flange joints is driven by thermal transients (e.g., >222°C/h temperature changes that reduce the bolt preload by 35% (Goyal 2024)), manufacturing defects (e.g., weld flaws in neck flanges (Noble et al. 2014)), or cyclic loading-induced gasket degradation. Shi et al. (2020) developed a two-source-four-sensor transient testing setup with transfer matrix analysis, achieving 95% accuracy in detecting leaks as small as 3 mm in diameter, which is critical for preventing toxic spills in chemical pipelines and protecting aquatic ecosystems.

Bohorquez et al. (2020) integrated fluid transient analysis with artificial neural networks (ANNs) to predict leak locations with a 2.32m average error, enabling rapid interventions to minimize resource loss in water distribution networks. Ahmad et al. (2023) advanced leak detection using one-dimensional convolutional neural networks (1D-CNNs) combined with acoustic emission data, improving sensitivity by 20% compared with traditional methods, a breakthrough for real-time monitoring in harsh environments where leaks could lead to catastrophic ecological damage.

Experimental studies by Jaszak (2021) showed that gasket leakage stabilised at 20% energy dissipation during the second bending cycle, providing insights into long-term sealing resilience and reducing the need for frequent gasket replacements. Gao and Kazama (2021) demonstrated that controlling sealing fluid viscosity through temperature management reduced leakage in flat-flange systems by 15%, an eco-efficient strategy to minimize waste from repeated maintenance.

BOLT PRELOAD INSTABILITY FOR GREEN MAINTENANCE AND PREDICTIVE STRATEGIES

Bolt preload instability caused by under-tightening (risking joint separation) or over-tightening (inducing stress overload) directly affects joint integrity. Argatov and Sevostianov (2010) pioneered electrical resistance measurements to detect preload loss, exploiting the contact interface resistance sensitivity to pressure changes for early loosening detection, a technique that reduces unnecessary inspections and associated carbon emissions from equipment shutdowns.

Wang et al. (2018) used piezoceramic transducers to monitor bolt loosening via energy dissipation analysis, achieving 90% accuracy in real-time detection, which is critical for preventing leaks in high-pressure systems without resorting to invasive maintenance. Schierl et al. (2023) compared yield-point controlled tightening (YCT) with traditional torque methods and showed that YCT reduced preload variability by 20%, minimising fatigue risks and extending bolt service life, thus reducing material waste from premature replacements.

Zhu et al. (2018) modeled the elastic interaction between bolts during tightening, revealing that sequential tightening caused 12% greater preload variation than star

patterns, a finding that informs sustainable assembly practices to optimize resource use. Grzejda et al. (2021) experimentally validated asymmetric multi-bolted connections under monotonic loads exhibited up to 25% preload deviations, highlighting the need for FEM-based tightening sequence optimisation to ensure a uniform load distribution and reduce component waste.

FATIGUE AND FRACTURE DYNAMICS: EXTENDING LIFESPAN FOR RESOURCE EFFICIENCY

Fatigue failure in MBF connections originates from manufacturing defects (e.g., coarse-grained welds) or repetitive stress cycles. Okorn et al. (2024) showed that even 0.03 mm flange gaps under eccentric loads increased bolt fatigue loads by 40%, drastically reducing service life. Lochan et al. (2019) identified a critical data gap in fatigue design standards for large bolts (e.g., M72 in offshore wind turbines), leading to over-conservative designs that waste 15–20% of material, an inefficiency FEM addresses by providing precise stress-life predictions.

Xu et al. (2022) proposed a residual fatigue life assessment framework for wind turbine bolts using pre-damaged M16 bolts under simulated marine loads to demonstrate that FEM-based models can predict the remaining life with 92% accuracy, enabling condition-based maintenance and reducing unnecessary replacement. In stainless-steel pipe-flange systems, Xu et al. (2022) linked DSS S31803 girth weld fractures to residual stresses from serrated gaskets, advocating stress-relief treatments that prevent premature failures and associated environmental risks from leaks.

Taghipour et al. (2021) analysed ammonia plant flange weld failures, correlated microstructural weaknesses with suboptimal welding parameters, and used FEM to show that improved heat input reduced coarse grain formation by 30% and enhanced joint strength and durability. These studies highlight the role of FEM in refining fatigue models to minimise material waste and ensure safety in high-consequence industries.

CORROSION DEGRADATION WITH MATERIAL SELECTION AND ENVIRONMENTAL STEWARDSHIP

Corrosion in flange systems driven by chemical aggression (e.g., CO_2 in hydrofluoric acid (Ji et al. 2023)) or material incompatibility (e.g., graphite gaskets accelerating stainless steel corrosion (Hakimian et al. 2024)) remains a major sustainability challenge. Hakimian et al. (2025) showed that wider flange gaps (≥1 mm) increased the corrosion rates by 50%, underscoring the need for gasket geometry optimisation to mitigate environmental exposure. Lyublinski et al. (2010) proposed volatile corrosion inhibitors (VCI)-embedded flange covers and desiccant systems, reducing moisture-induced corrosion by 40% and extending service life without harmful coatings, aligning with green technology goals.

Ossai et al. (2015) analyzed pipeline failures from sweet corrosion and microbiologically induced corrosion (MIC), advocating for predictive maintenance using FEM-based models to monitor environmental stressors, a strategy that reduces unplanned downtime by 30% and prevents toxic releases into soil and water bodies. Novikov et al. (2018) developed a corrosion resistance prediction technique using FEM, enabling data-driven material selection to reduce degradation risks in aggressive environments, thus minimizing waste from frequent replacements and remediation efforts.

Table 1 summarises the key defects in MBF connections, their sustainability implications, and FEM-driven mitigation strategies discussed in this section.

TABLE 1. Common Defects in MBF connections and FEM-driven mitigation strategies

Defect type	Main technical causes	Sustainability impact	FEM-driven mitigation	Key finding
Uneven load distribution	Flatness deviation; asymmetric loading; support misalignment	Material waste; leakage risk; reduced fatigue life	Support layout optimization; bolt-load analysis; tolerance control	Optimized support layout reduces leakage risk; improved washers extend bolt fatigue life
Leakage mechanisms	Thermal transient; weld defect; gasket fatigue	Fluid loss; contamination; shutdown waste	Thermo-mechanical modelling; leakage-pressure prediction; sensor integration	Transient and acoustic methods improve early leakage detection
Bolt preload instability	Under-tightening; over-tightening; poor tightening sequence	Unplanned downtime; bolt/gasket replacement; higher maintenance waste	Preload monitoring; tightening-sequence optimization; YCT control	Controlled tightening reduces preload variation and improves joint reliability

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Defect type	Main technical causes	Sustainability impact	FEM-driven mitigation	Key finding
Fatigue and fracture	Cyclic loading; geometric gap; manufacturing defect	Premature replacement; safety risk; downtime	Fatigue-life prediction; residual-life assessment; stress-based design	Small flange gaps can significantly increase bolt fatigue demand
Corrosion degradation	Chemical attack; crevice corrosion; material incompatibility	Flange replacement; coating waste; soil/water contamination	Material selection; corrosion prediction; environmental-stress modelling	Gasket/flange material compatibility reduces corrosion-driven failure

FINITE ELEMENT METHOD AS A CATALYST FOR SUSTAINABLE DEFECT MITIGATION IN MULTI-BOLTED

FEM has revolutionized the analysis and design of MBF systems, offering the dual benefits of technical precision and sustainability alignment. By simulating complex mechanical, thermal, and environmental interactions, FEM enables engineers to develop solutions that enhance structural integrity while advancing resource efficiency, environmental safety, and green maintenance, which are the core tenets of sustainable engineering. This section synthesises cutting-edge FEM applications across key defect categories and demonstrates how this technology addresses both technical challenges and global sustainability goals.

FATIGUE AND DYNAMIC BEHAVIOR: EXTENDING LIFESPAN THROUGH PRECISION

Fatigue failure driven by cyclic loads and geometric imperfections is the primary cause of material waste and unplanned downtime in MBF connections. FEM's high-fidelity modelling of stress–strain distributions has been pivotal in refining fatigue life predictions and reducing over-engineering. Novoselac et al. (2014) pioneered dynamic load analysis in heat-treatable steel-bolted joints, revealing that local stress states near thread roots significantly influence fatigue initiation, a finding that guided the design of more durable bolt geometries, minimizing premature replacements and associated material waste.

Ji et al. (2023) used FEM to quantify the impact of flange flatness deviations on fatigue damage in offshore wind turbines, where large bolts are subjected to variable marine loads. Their models showed that tower-sided gaps increased fatigue cycles by 18% in fixed-bottom turbines, underscoring the need for geometric tolerance control to extend the component lifespan and reduce waste in renewable energy infrastructure.

Okorn et al. (2021) further demonstrated that FEM accurately predicts bolt bending loads, a common cause of fatigue, revealing that analytical methods overestimate stresses by up to 25% under low working loads. By correcting these inaccuracies, FEM-driven designs reduce material usage while ensuring safety, thereby aligning with circular economy principles.

STRUCTURAL HEALTH MONITORING: DATA-DRIVEN PREDICTIVE MAINTENANCE

Structural Health Monitoring (SHM), enabled by FEM, transforms reactive maintenance into a strategic, low-waste practice by detecting preload instability and bolt loosening in real time. Grzejda et al. (2022) developed an FEM-based framework to monitor bolt forces in multi-bolted joints, validating that preload deviations can be detected with <6% error compared to experimental tests. This precision allows for targeted interventions to avoid unnecessary component replacement and associated environmental and economic costs. Figure 2 shows an FEM-based model of a multi-bolted joint and a single fastener.

In industrial applications, Sanli et al. (2025) integrated FEM with piezoresistive sensors to optimise the placement of their BoltWISE sensor, which detects loosening torque with high sensitivity. By simulating stress distributions during tightening and loosening, they ensured that the sensor responded within 0.9–1.3 µm displacement, enabling early detection and reducing downtime-related carbon emissions. Such solutions exemplify how FEM supports green maintenance, where data replace guesswork and minimise resource waste and operational disruptions.

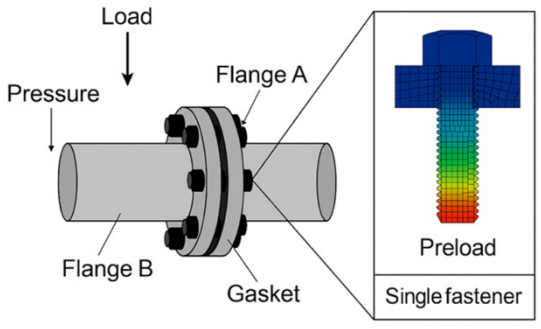


FIGURE 2. FEM-based model of the multi-bolted joint and single fastener

DESIGN OPTIMIZATION FOR PERFORMANCE AND RESOURCE EFFICIENCY

FEM-based design optimisation provides a systematic pathway for improving the performance of MBF connections by linking the bolt preload, flange stiffness, gasket compression, contact pressure distribution, support-induced loading, and material efficiency within a single numerical framework. Unlike conventional design practices that frequently rely on conservative empirical margins, FEM allows engineers to identify the actual load-transfer mechanism from bolt tightening to gasket seating and flange deformation (Sidun & Łukaszewicz 2017).

This is particularly important because excessive conservatism may increase the flange thickness, bolt size, material consumption, and embodied carbon, whereas insufficient stiffness or non-uniform preload may lead to leakage, fatigue damage, premature maintenance, and unnecessary component replacement.

In gasketed flange joints, the optimisation objective is not simply to increase strength but to maintain a stable sealing condition while avoiding excessive local stress. Jaszak and Adamek (2019) combined FEM with analytical calculations to determine the optimal assembly torque for gasketed joints, showing that contact stress mapping can support sealing integrity while reducing unnecessary gasket material usage.

Recent work by Elkhlaidy et al. (2023) reinforced this point by demonstrating that flange geometric configuration, bolt stress, gasket seating, elastic–plastic flange behaviour, nonlinear gasket response, and flange–gasket contact should be assessed together during assembly. Their 3D FEA-based approach highlighted that excessive bolt pre-stress may improve initial gasket compression but can also promote local plastic strain, whereas insufficient pre-stress may leave parts of the gasket under-compressed and susceptible to leakage (Abid et al. 2018).

The same optimisation logic applies to the flange stiffness and bolt-load distribution. Blachowski and Gutkowski (2016) showed through FEM analysis of circular flange-bolted connections that bolt pre-tension and flange thickness strongly influence connection stiffness. This finding is significant for sustainable design because stiffness improvement does not always require excessive material addition; instead, the flange thickness, bolt arrangement, and load path can be refined to achieve a reliable structural response with more efficient steel usage.

Zhong et al. (2025) also demonstrated that tightening sequence directly affects the final uniformity of bolt load in MBF structures. Their single-step tightening method demonstrated that bolt-load uniformity can be improved through controlled preload sequencing, which reduces localised overloading, under-compressed gasket zones, and preload scatter.

Design optimisation must also consider combined loading rather than only the assembly load. Khan and Ahmed (2023) reported that gasketed bolted flange joints subjected to combined internal pressure, axial loading, and bending may experience significant variation in bolt and gasket stresses, with bolt stress scatter reaching approximately 18% of the target value. This is relevant to MBF sustainability because non-uniform bolt stress can increase the local fatigue demand, accelerate gasket degradation, and shorten the inspection or maintenance intervals.

Similarly, Nelson et al. (2023) emphasised that bolted flange joints are affected by material nonlinearity, geometric nonlinearity, load redistribution, and relaxation, all of which influence both the structural integrity and sealing behaviour. These findings indicate that flange optimisation should not be limited to the nominal pressure capacity but should include contact stability, bolt-load retention, gasket relaxation, and service-induced deformation.

For piping systems carrying corrosive or hazardous fluids, FEM-based design optimisation extends beyond the flange to include the surrounding pipe support and installation conditions. Lu et al. (2021) used FEM to identify support misalignment as a root cause of leakage in hydrofluoric acid pipeline flange connections. By repositioning the supports and reducing the bending moments at the flange, the leakage risk can be reduced without relying only on thicker components or more expensive corrosion-resistant materials. This shows that the optimised design is a system-level activity involving the flange geometry, support layout, bolt preload, gasket response, and pipe alignment.

The relevance of optimisation is also supported by recent welding-focused studies, in which geometric control has direct implications for structural performance and resource efficiency. Sohel et al. (2025) demonstrated that Taguchi-optimized GTAW parameters can reduce SS316L pipe weld root height to below 2 mm, improving weld precision and joint reliability while reducing the risk of flow disturbance and unnecessary repair.

Sohel et al. (2026a) further emphasized that welding current, voltage, travel speed, shielding gas, heat input, and joint preparation interact to influence bead morphology, heat-affected zone evolution, mechanical performance, and weld-root geometry in critical piping systems.

Most importantly, the FEA-based study by Sohel et al. (2026b) demonstrated that weld root reinforcement above 2.0 mm increases von Mises, hoop, longitudinal, and radial stress gradients, whereas reinforcement at or below 2.0 mm provides smoother load transfer and reduced

stiffness discontinuity across the weld interface. Although these studies focused on welded pipe joints rather than bolted flange joints, they supported the same design principle: controlling the local geometry and load transfer is essential for reducing stress concentration, improving reliability, and minimising avoidable material and maintenance waste.

Overall, FEM-driven design optimisation improves the MBF performance through four connected mechanisms: redistribution of local stress concentration, stabilisation of gasket contact pressure, reduction of bolt preload scatter, and minimisation of unnecessary material use. These mechanisms directly address the relationship between technical challenges and material waste. Poorly optimised flange joints may require repeated gasket replacement, excessive bolt tightening, premature maintenance, heavier flange sections, or emergency repairs after leakage.

In contrast, the optimised FEM-based design enables performance improvement through better geometry, preload control, contact pressure management, support layout, and verified load-transfer behaviour rather than through material increase alone. Therefore, FEM should be viewed not only as a numerical validation tool but also as a sustainability-oriented design method for achieving reliable, leak-resistant, and resource-efficient MBF systems.

LEAKAGE PREDICTION AND ENVIRONMENTAL PROTECTION

Leakage in gasketed joints, a major threat to ecological balance, is effectively mitigated through FEM's ability to model thermal-mechanical interactions. Jaszak et al. (2022) developed an FEM-based methodology to predict leakage under pipeline deformation, showing that gasket surface pressure uniformity improved by 22% with optimised flange geometry, which is critical for preventing contaminant spills in water and chemical systems. Beghini et al. (2015) advanced this field by combining fracture mechanics with FEM to predict leakage pressure in metal-to-metal flanges, providing a tool to design leak-resistant interfaces without excessive material reinforcement.

In high-temperature environments, FEM helps manage the thermal transients that cause preload loss and gasket failure. Goyal (2024) used FEM to model temperature-induced bolt stress relaxation, demonstrating that thermal spacers reduce plastic deformation by 35%, extend gasket service life, and avoid environmentally harmful leaks. These applications highlight FEM's role in safeguarding ecosystems while reducing the lifecycle costs of reactive remediation.

BOLT FORCE DISTRIBUTION AND MECHANICAL EFFICIENCY

Understanding the bolt force distribution is critical for minimising fatigue and material waste. Grzejda (2019) compared rigid and flexible bolt models using FEM and found that flexible models (e.g., spider bolts) improved force prediction accuracy by 16–19% over traditional rigid-body models. This precision allows engineers to reduce the number of bolts without compromising safety, which reduces material usage and manufacturing emissions.

To improve the visual clarity of the bolt-force redistribution mechanisms, Figure 3 illustrates four typical force-distribution cases in MBF connections. These include a uniform preload distribution under ideal tightening, non-uniform preload distribution caused by tightening-sequence effects or geometric imperfections, asymmetric distribution under external bending or support misalignment, and load redistribution after bolt loosening. The schematic highlights that changes in the bolt preload are directly reflected in the gasket contact pressure variation, which influences sealing reliability, fatigue susceptibility, and long-term joint integrity.

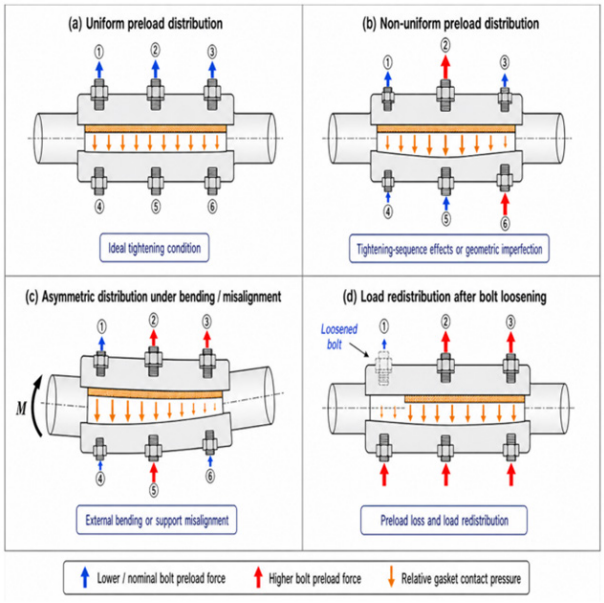


FIGURE 3. Schematic representation of typical force-distribution cases in MBF connections: (a) uniform preload distribution under ideal tightening, (b) non-uniform preload distribution caused by tightening-sequence effects or geometric imperfections, (c) asymmetric distribution under external bending or support misalignment, and (d) load redistribution after bolt loosening. Upward arrows indicate the relative bolt preload force, whereas downward arrows indicate the relative gasket contact pressure.

Sun et al. (2022) further developed an FEM-based dynamic loosening detection method using acceleration signals, which identified preload loss with 95% accuracy. By linking bolt-force dynamics to structural vibrations, this approach supports predictive maintenance in high-reliability systems, such as missiles and nuclear pipelines, where failure risks are both technical and environmental.

To underscore the transformative impact of FEM on sustainable engineering practices, Table 2 compares the key performance metrics of traditional approaches with FEM-driven solutions, highlighting tangible gains in resource efficiency, environmental safety, and maintenance optimisation.

TABLE 2. Performance Comparison of Traditional vs. FEM-Driven Solutions

Application	Traditional approach	FEM-driven approach	Sustainability benefit	Representative finding
Flange support layout	Empirical support placement; conservative safety factors	Zero-bending-moment positioning using FEM	Lower leakage risk; reduced overdesign	Support optimization reduces flange bending and leakage susceptibility
Bolt fatigue assessment	Simplified analytical stress models	Local stress–strain and fatigue modelling	Longer bolt life; fewer replacements	FEM captures bolt bending and local fatigue-critical zones
Gasket sealing optimization	Trial-and-error gasket selection	Contact-pressure mapping	Less gasket waste; improved sealing	Optimized gasket pressure improves leak-tightness
Preload monitoring	Periodic manual inspection	Sensor-assisted FEM and preload tracking	Less downtime; targeted maintenance	FEM supports early detection of preload loss
Corrosion protection	Reactive coating or replacement	Material compatibility and corrosion-risk modelling	Reduced coating use; longer service life	FEM supports targeted corrosion mitigation

LITERATURE REVIEW SUMMARY

FEM has emerged as a game changer in the analysis and design of MBF connections and piping systems. This provides researchers and engineers with powerful computational means to simulate intricate behaviours and optimise structural integrity. This literature review consolidates the key findings from recent studies, highlighting the wide-ranging applications of FEM in addressing critical issues related to MBF connections. These applications are closely related to the goals of sustainable engineering, which aims to enhance resource efficiency, environmental protection, and maintenance.

FATIGUE AND DYNAMIC BEHAVIOR

The fatigue behaviour of bolted joints under dynamic loads has been a significant area of focus. Novoselac et al. (2014) were pioneers in this field. They developed a multibody dynamic model to simulate the stress distribution in detailed threaded connections made of heat-treatable steel (30CrNiMo8). Their work was fundamental in understanding the effect of dynamic loads on the lifespan of flange connections. This emphasises the crucial role of local stress-strain states and the importance of detailed modelling in accurate fatigue assessment. This not only improves the understanding of fatigue mechanisms but also has implications for reducing material waste, as more accurate models could lead to better-designed components with longer lifespans.

Building on this foundation, Ji et al. (2023) extended their research to offshore wind turbines (OWTs). They analysed the impact of the initial flatness divergence on the flange connection. Their findings are significant in the context of renewable energy infrastructure. For instance, they found that flange-sided and tower-sided gaps significantly increased fatigue damage, particularly in fixed-bottom turbines. This insight is crucial for the sustainable operation of OWTs, as it helps optimise the design and maintenance of these structures. Engineers can develop strategies to prevent premature failure by considering geometric imperfections in fatigue assessments, thereby reducing the need for frequent replacements and associated material waste.

Okorn et al. (2021) further investigated the additional loads and fatigue life of preloaded bolts. They demonstrated that FEM offers a more accurate representation of the stress state and fatigue life of a bolt than analytical methods, particularly when considering the influence of bolt bending. This is important for ensuring the reliability of the flange connections. Underestimating or overestimating the bolt stress can lead to component failures or over-engineering, both of which are detrimental to sustainability. FEM

improves the accuracy of stress and fatigue assessments, helping engineers design more efficient and durable components while minimising material usage and environmental impact.

Okorn et al. (2024) highlighted the substantial impact of geometric imperfections on bolt fatigue. They showed that even minor deviations can significantly reduce the fatigue life. These findings emphasise the need for precise manufacturing and quality control measures. In the context of sustainable engineering, preventing fatigue failure through accurate modelling and design can lead to significant savings in terms of resources and energy. By using FEM to identify and mitigate the effects of geometric imperfections, engineers can extend the lifespan of MBF connections and reduce the frequency of replacements and associated environmental costs of these connections.

STRUCTURAL HEALTH MONITORING

FEM has proven to be invaluable for SHM applications involving multi-bolted joints. Grzejda et al. (2022) utilised FEM to determine the bolt preload and analysed the effects of different preloading sequences on the forces in the remaining bolts. Their study validated the accuracy of the FEM models, with discrepancies between the experimental and FEM results not exceeding 6%. This level of accuracy is crucial for SHM because it enables the precise monitoring of bolt preload. Engineers can take proactive measures to prevent bolt loosening and subsequent failures by accurately predicting preload changes. This not only improves the safety and reliability of MBF connections but also reduces the need for reactive maintenance, which is often resource intensive.

Sanli et al. (2025) introduced a novel technique for real-time monitoring of bolted joint loosening torque using a piezoresistive pressure-sensitive layer. They employed FEM simulations to optimise the sensor placement. This ensures a rapid response during bolt tightening and loosening, thereby enhancing the reliability of loosening detection in industrial settings. In a sustainable engineering framework, real-time monitoring can reduce unplanned downtime. By detecting bolt loosening early, maintenance can be scheduled at convenient times, thereby minimising disruptions to production processes. This leads to increased productivity and reduced energy consumption associated with unplanned shutdowns.

DESIGN AND STRENGTH ANALYSIS

FEM plays a crucial role in optimising the design and strength analysis of flange connections. Jaszak and Adamek (2019) integrated FEM with analytical calculations to determine the optimal assembly torque for different gasket types. This approach provides detailed insights into the contact stress distribution and the safety factors. By optimising the assembly torque, engineers can ensure that gasketed joints have the appropriate level of tightness, thereby reducing the risk of leakage. Simultaneously, they can minimise the use of gasket materials, leading to material savings and cost reduction. This is an example of how FEM can be used to balance the performance and resource efficiency in design.

Blachowski and Gutkowski (2016) used FEM to assess the structural behaviour of telecommunication towers with circular flange-bolted connections. They revealed the significant influence of bolt pre-tension and flange thickness on connection stiffness. This knowledge is essential for designing lighter and more durable structures in the future. By optimising these parameters, engineers can reduce the amount of steel used in the construction of telecommunication towers, which not only saves material resources but also reduces the environmental impact associated with the production and transportation of steel.

Lu et al. (2021) addressed leakage issues in pipelines transporting corrosive substances by using FEM to analyze internal forces and optimize support positioning. This significantly reduces the bending moment and enhances sealing performance. In sustainable engineering, preventing pipeline leakage is crucial for environmental protection and sustainability. By using FEM to optimise pipeline design, engineers can avoid the release of hazardous substances into the environment, thereby reducing the need for costly environmental remediation.

FAILURE MECHANISMS

Failures in MBF systems are rarely caused by a single isolated factor. Instead, it usually develops through the interaction of bolt preload loss, flange deformation, gasket contact degradation, cyclic loading, corrosion, local geometric discontinuity, and service-induced vibrations. Therefore, the failure mechanism should be interpreted as a progressive process rather than a final visible defect. FEM is valuable in this context because it allows the dominant failure driver to be separated from secondary effects by evaluating the stress redistribution, contact pressure loss, bolt-force variation, flange rotation, and local deformation under defined loading conditions.

One important failure pathway is the bolt preload instability. During assembly, tightening one bolt may alter the preload in the neighbouring bolts because of the elastic interaction within the flange–bolt–gasket system. When

the final preload distribution becomes non-uniform, some bolts may carry higher stress, whereas others may provide insufficient clamping force. This creates two simultaneous risks: local overstress in the highly loaded bolts and reduced gasket contact pressure in the under-clamped regions. Under repeated pressure fluctuations, vibrations, or thermal cycling, this uneven preload condition can gradually develop into bolt loosening, gasket unloading, local separation, and leakage. Recent studies on subsea pipeline connector bolts have shown that preload scatter can significantly influence the bolt fatigue life when internal pressure is combined with vortex-induced vibration, confirming that preload variation is not only an assembly quality issue but also a long-term fatigue reliability concern.

Bolt loosening is another critical failure mechanism in MBF systems, especially where the joint is exposed to vibration, shock, rotating equipment, or fluctuating pressure. Loosening changes the contact stiffness of the joint and reduces the energy transfer capacity of the flange interface. Once the clamping force drops below a stable threshold, the joint may experience micro-slips, fretting, increased dynamic response, and accelerated fatigue damage.

Chen et al. (2025) showed that multi-bolt loosening in flange pipe structures can be identified through nonlinear guided-wave energy transmission, where the transmitted energy changes with bolt preload and contact state. This supports the view that bolt loosening is strongly governed by contact nonlinearity and is closely linked to the degradation of the interface stiffness.

The second pathway is flange rotation and local joint separation. Under internal pressure, external bending, pipe misalignment, support displacement, or thermal expansion, the flange faces may rotate relative to one another. Even when the average bolt stress remains acceptable, local separation may occur at a part of the gasket interface, creating a preferential leakage path.

This mechanism is difficult to detect using global pressure ratings or torque values alone because the critical condition is governed by local contact pressure and deformation. FEM helps reveal this mechanism by simultaneously mapping the gasket contact pressure, flange displacement, gap opening, and bolt stress at the same time. Therefore, flange failure should not be judged only by the maximum stress but also by the stability of the sealing interface and continuity of the contact zone.

Fatigue is another dominant mechanism, particularly in MBF systems subjected to dynamic services. The fatigue life of bolts depends on the preload level, bolt stiffness, flange stiffness, external cyclic load, load transfer path, and local bending stress. Okorn et al. (2024) emphasized that the amplitude of bolt load in dynamically loaded flange joints is influenced by bolt resilience, clamped-part stiffness, working-load magnitude, preload, and geometric imperfections.

This is important because even a small local gap or stiffness imbalance may increase the alternating stress range in the selected bolts, causing fatigue initiation before obvious flange damage occurs. In this sense, FEM-based fatigue analysis is essential because it identifies the localised stress concentration at bolt shanks, thread roots, flange holes, and flange transition zones that cannot be captured adequately by average nominal stress calculations.

Failure may also occur due to stiffness degradation caused by partial bolt failure. (Liu et al. 2023) investigated flange connections with bolt failure and showed that bolt failure changes the local stiffness and geometric characteristics of the flange connection, which can influence the dynamic response of the connected system. Their work is relevant to MBF systems because the failure of one or several bolts not only reduces clamping capacity locally, but also redistributes the load to the remaining bolts and introduces asymmetric stiffness into the joint. This may accelerate the failure sequence, particularly in systems exposed to vibration or cyclic loading, where stiffness asymmetry can increase local dynamic amplification.

Torsional excitation and thread-level behaviour can further contribute to loosening and connection failure. Pan et al. (2025) developed dynamic models for one-bolted and multi-bolted connection systems under torsional excitation and showed that thread pitch, excitation amplitude, excitation frequency, bolt stiffness, connected-part stiffness, bolt number, and connected-part thickness influence anti-loosening performance. Although their application is based on aeroengine bolted connection structures, the mechanism is transferable to MBF systems because the same physical factors—contact stiffness, preload retention, thread interaction, and excitation—control the stability of bolted joints under dynamic loading.

The failure mechanisms in MBF systems may also be affected by the welded-joint quality and local geometric discontinuities in the connected piping. In welded pipe-flange assemblies, weld root geometry, residual stress, misalignment, and local reinforcement can influence the stress field entering the flange region.

Corrosion and material degradation may further accelerate flange failure by reducing the sealing surface integrity and altering the contact conditions. In corrosive or chemically aggressive environments, gasket-induced galvanic effects, crevice corrosion, surface pitting, and local material loss can reduce the effective gasket seating area. Once the sealing face is locally damaged, even the correct bolt preload may not restore uniform gasket compression.

FEM can support this type of failure assessment by

modelling the reduced contact area, surface loss, local stiffness reduction, and stress redistribution. This allows the analyst to determine whether leakage or joint degradation is primarily caused by mechanical overload, preload loss, corrosion damage, or a combination of mechanical and environmental deterioration.

Overall, the reviewed studies show that FEM is not only a tool for predicting ultimate failure loads but also a mechanism-based diagnostic method for explaining how failure initiates and propagates. If the dominant mechanism is the preload scatter, the corrective action should focus on the tightening sequence, preload verification, and bolt-load monitoring. If loosening is dominant, vibration control and real-time looseness detection may be required. If the flange rotation or local separation governs the failure, the flange stiffness, gasket selection, and support alignment should be improved. If corrosion-assisted degradation is the main driver, sealing surface protection and material compatibility become more important. Therefore, FEM strengthens failure analysis by connecting observable damage to root-cause mechanisms and supporting targeted, sustainable maintenance decisions rather than broad component replacement.

LEAKAGE PREDICTION

Leakage prediction is one of the most important applications of FEM in MBF systems because leakage is governed not by a single global parameter but by the combined interaction of bolt preload, gasket compression, flange rotation, internal pressure, pipe deformation, temperature variation, surface condition, and material relaxation. Conventional leakage assessments often depend on pressure ratings, empirical gasket factors, or nominal bolt torque.

Although these approaches are useful for design practice, they cannot fully capture the local contact pressure variation that controls the actual initiation of leakage. FEM improves this assessment by directly modelling the gasket–flange contact interface and identifying regions where the local sealing pressure falls below the minimum pressure required to maintain a leak-tight performance.

Jaszak et al. (2022) developed a methodology for predicting leakage in gasketed flange joints under pipeline deformation and validated FEM model using experimental data. Their work is particularly relevant because it shows that the deformation of a connected pipeline can disturb both the radial and circumferential gasket stress distributions.

In practical piping systems, flange joints rarely operate under internal pressure alone; pipe settlement, support misalignment, vibration, thermal expansion, and external bending can impose additional moments on the joint. These moments may unload one region of the gasket while overcompressing another region. Consequently, leakage may initiate locally at the weakest contact zone, even when the average gasket compression appears adequate. Therefore, leakage prediction should be based on local contact pressure continuity rather than nominal assembly torque or average gasket seating stress alone.

Beghini et al. (2015) proposed an analytical model for leakage pressure in bolted metal-to-metal flanges and validated it using FEM simulations and experimental tests. This contribution remains important because it demonstrates how FEM can support simplified leakage models by providing local stress and deformation information that cannot be obtained from global calculations.

For metal-to-metal flange interfaces, leakage is strongly influenced by local openings, partial crack-like separations, and contact loss at the sealing surface. FEM helps identify these partial opening zones and allows the leakage pressure to be related to the actual mechanical condition of the joint instead of relying only on idealised sealing assumptions.

Recent studies have shown that the bolt axial force plays a central role in preventing leakage. Wang et al. (2024) investigated the sealing performance of high-pressure flanges using a magnetic measurement method to determine the bolt axial force. Their study highlighted that high-pressure flange sealing can fail when the bolt pre-tension is insufficient, leading to unstable pressurisation or leakage. This finding is important for FEM-based leakage assessments because the bolt axial force is the primary source of gasket compression.

If the applied bolt force is too low, the gasket may not reach the required seating stress; if it is too high, gasket crushing, local yielding, or accelerated relaxation may occur. Thus, FEM leakage models should evaluate not only whether the gasket is compressed, but also whether the compression remains within an effective sealing window during assembly and operation.

The gasket material and geometry also influence the leakage resistance. Jaszak (2019) examined symmetric and asymmetric semi-metallic gasket core shapes and showed through experimental testing and FEM-based numerical calculations that gasket core geometry affects the tightness level of bolted flange joints. The asymmetric core produced a higher strain on the graphite sealing layer and a more uniform strain distribution on the core ridge.

This is significant because the leakage performance depends not only on the bolt load magnitude but also on how effectively the gasket converts the bolt load into a stable sealing pressure. FEM is useful for comparing gasket designs because it can map the strain, contact pressure, and

deformation at local sealing regions before physical testing or field application.

Leakage prediction also requires attention to monitoring and the long-term degradation of services. Cloostermans et al. (2025) reviewed monitoring challenges and technologies for bolted flange connection leakage and emphasised that leak tightness depends strongly on achieving appropriate gasket surface pressure during installation and maintaining it during operation. This aligns with the FEM-based view that leakage risk evolves as the preload relaxes, gasket material creeps, surface roughness changes, and service loads fluctuate. When FEM is integrated with monitoring data, such as bolt-load measurements, acoustic emissions, guided waves, pressure decay, or temperature records, leakage prediction can move from static design verification to predictive maintenance.

Thermal effects further complicate the leakage prediction. Temperature gradients may cause differential expansion between bolts, flanges, and gaskets, whereas gasket creep and bolt relaxation can progressively reduce the clamping force. In high-temperature or cyclic operations, the initial assembly preload may not represent the actual sealing condition during service.

FEM-based thermomechanical analysis can simulate how temperature changes modify bolt stress, flange rotation, gasket compression, and contact pressure distribution. This is particularly important in chemical plants, process piping, wastewater treatment systems, and other industrial environments where start-up, shutdown, pressure fluctuations, and corrosive media may act together.

Overall, FEM-based leakage prediction contributes to sustainable engineering by allowing designers to identify vulnerable leakage zones before field failures occur. It supports the comparison of gasket materials, flange stiffness, bolt patterns, tightening strategies, operating pressure, thermal effects, and support conditions under consistent boundary conditions.

When combined with experimental validation and monitoring technologies, FEM can help determine whether the leakage risk is governed by inadequate preload, gasket relaxation, flange rotation, pipe deformation, thermal mismatch, or sealing surface degradation. This mechanism-based prediction enables targeted corrective actions, reduces unnecessary shutdowns and gasket replacements, prevents environmental release, and improves the long-term reliability of the MBF systems.

BOLT FORCE DISTRIBUTION

FEM has provided valuable insights into the bolt-force distribution in multi-bolted systems, which is closely related to the reliability and resource efficiency of MBF connections. Grzejda (2019) compared different models for analysing bolt forces under operational loads. They found that flexible bolt models (SB) improved the accuracy of predicting operational forces.

This accuracy is crucial for designing safe multi-bolted systems. Engineers can optimise bolt layouts and reduce the number of bolts required without compromising safety using more accurate models. This leads to material savings and cost reductions in the manufacturing and assembly of MBF connections.

Sun et al. (2022) established a new method for detecting dynamic loosening based on acceleration signals. Their approach demonstrated the superiority of FEM in predicting the structural behaviour under complex loading conditions. In the context of sustainable engineering, the early detection of dynamic loosening can prevent component failure and associated downtime. This method allows for proactive maintenance, reducing the need for emergency repairs and associated resource waste. It also helps ensure the long-term reliability of MBF connections, thereby contributing to the overall efficiency of industrial systems.

To enhance the clarity of FEM's holistic role of FEM in sustainable engineering, Figure 4 visualises the technical pathway from defect analysis to the realisation of eco-efficient solutions. This schematic outlines how FEM integrates mechanical modelling with sustainability goals, translating insights from stress distribution and deformation behaviour into actionable strategies for design optimisation and predictive maintenance of the equipment.

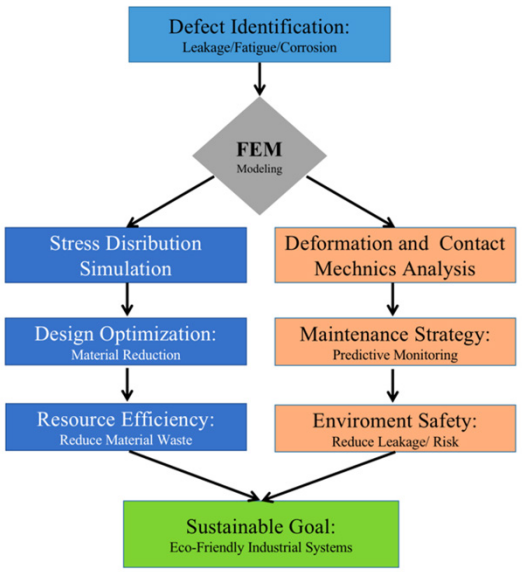


FIGURE 4. Workflow of FEM-Driven Sustainable Engineering for Multi-bolted Flanges

By mapping the journey from identifying critical issues, such as leakage and fatigue, to achieving resource efficiency and environmental safety, this figure highlights the interdisciplinary value of FEM in modern industrial infrastructure.

CONCLUSION

MBF connections are vital to industrial infrastructure; however, their reliability is challenged by complex loads, thermal variations and environmental stresses. This review explores how FEM serves as a transformative tool that enables precise analyses and sustainable solutions for critical defects, such as uneven load distribution, leakage, and fatigue. By simulating the mechanical behaviour and optimising the designs, FEM enhances the structural integrity while improving resource efficiency, environmental protection, and proactive maintenance practices.

CORE CONTRIBUTIONS OF FEM

The FEM has enabled detailed modelling of stress distributions and fatigue mechanisms, allowing engineers to design components with extended lifespans and reduced material waste. SHM supports the real-time detection of preload instability and bolt loosening, facilitating targeted maintenance that minimises downtime and operational waste. Design optimisations using FEM have also improved the sealing performance and reduced the material usage in gaskets and flanges, thereby balancing safety with eco-efficient designs.

In FEM-based bolt modelling, the accuracy of the predicted flange response depends strongly on how the bolt, nut, washer, gasket, and flange interfaces are represented. Most reviewed studies modelled bolts as simplified beam or spring elements, rigid connector elements, or detailed three-dimensional solid elements, depending on the required level of accuracy.

Simplified bolt models are useful for global load-distribution studies because they reduce the computational cost, whereas detailed solid bolt models are more suitable for evaluating local stress concentration, thread-root stress, bolt bending, and preload relaxation.

Typical modelling conditions include the assignment of elastic or elastic–plastic material properties, definition of bolt pretension or axial preload, contact interaction between flange faces and gasket surfaces, frictional contact at washer and nut-bearing areas, and boundary constraints representing internal pressure, external bending, thermal loading, or pipe-support effects. Mesh refinement is usually required around bolt holes, thread engagement regions, gasket contact surfaces, and flange hub transitions because these locations govern the local stress concentration and leakage susceptibility.

Therefore, a reliable FEM assessment of MBF systems should not only rely on the nominal bolt force but should also consider the preload sequence, contact stiffness, friction coefficient, gasket compressibility, geometric imperfection, and service-induced load combinations.

These modelling conditions are important because an oversimplified bolt representation may underestimate the local stress concentration or fail to capture the redistribution of the preload among adjacent bolts. Conversely, an excessively detailed model may increase the computational cost without significantly improving the global design decisions. Hence, the appropriate bolt modelling strategy should be selected according to the objective of the analysis, whether it is global load sharing, leakage prediction, fatigue assessment, preload monitoring, or failure mechanism interpretation.

PATHWAYS FOR FUTURE INNOVATION

Emerging research opportunities have focused on integrating the FEM with cutting-edge technologies to further enhance MBF reliability. Developing self-healing materials could offer autonomous solutions for leakage, whereas refining fatigue models for large bolts in harsh environments could address long-standing design issues.

Additionally, the combination of FEM with machine learning and real-time monitoring systems holds promise for creating adaptive infrastructure that proactively responds to operational stresses and improves predictive maintenance and ecological safety.

However, several important research gaps remain in the literature. First, few studies have integrated FEM with self-healing material modelling to evaluate whether autonomous sealing or crack-closure mechanisms can improve the long-term reliability of MBF systems. Second, few studies have combined FEM with real-time adaptive control systems capable of updating the bolt preload, gasket contact pressure, or leakage risk predictions during service.

Third, many expansion studies still focus on isolated mechanical or thermal loading conditions, whereas fewer investigations consider coupled effects involving preload relaxation, gasket aging, corrosion degradation, vibration, and pipe-support misalignment. Finally, experimentally validated digital twin frameworks that can link FEM predictions with sensor-based monitoring data for predictive maintenance and sustainable asset management are required.

FINAL PERSPECTIVE

FEM provides a practical bridge between structural reliability, leak prevention, and sustainable maintenance in MBF systems. By clarifying how the bolt preload, gasket contact pressure, flange deformation, fatigue loading, and corrosion-related degradation interact, FEM enables more targeted design decisions and reduces the reliance on conservative overdesign or reactive replacement.

As industrial infrastructure moves toward greener and more resilient operations, FEM-informed design, monitoring, and maintenance strategies will remain essential for improving joint integrity, minimising material waste, and supporting safer long-term asset performance.

ACKNOWLEDGEMENT

None.

DECLARATION OF COMPETING INTEREST

None.

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