FRONTIERS IN POWER:

ENGINEERING SOLUTIONS EMERGING FROM RECENT ASSET RELIABILITY RESEARCH

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Bolted Assembly for Faster and Lower Cost Deployment of Floating Offshore Wind Turbine Foundations

Analysis of Legacy vs Emerging Surface Treatments for Improving Wear Resistance in Hydro Turbines

An Integrated Approach to Predicting Structural Damping of 3D-Printed Components in Hydrogen-Ready Gas Turbines

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ENG. ALESSIO CASCINO, Ph.D.

TECHNICAL REVIEWERS:

CYRIL CADOUX
Technical Director, Nord-Lock
Nord-Lock Group

SPENCER FARUQUEE
Application Engineer, Nord-Lock
Nord-Lock Group

ANDERS KNUTSSON
Product/Project Manager, Nord-Lock
Nord-Lock Group

BOLTED ASSEMBLY FOR FASTER AND LOWER COST DEPLOYMENT OF FLOATING OFFSHORE WIND TURBINE FOUNDATIONS

ALDERT OTTER, PH.D. & NAVID BELVASI, PH.D.

Aldert Otter brings 25 years of experience to his role as Senior Offshore Wind Consultant at Electricity Supply Board (ESB) Ireland. His career spans floating wind engineering, T&I, offshore wind construction and captaincy of anchor handling vessels. He holds a BSc in Nautical Science, an MSc in Offshore Renewable Engineering, and a PhD in Applied Floating Offshore Wind Physics.

Navid Belvasi is a Senior Engineer at Electricity Supply Board (ESB) Ireland, specializing in offshore wind engineering. With over 12 years of experience, he has expertise in offshore structural design and analysis, floating offshore wind technology, and offshore hydrodynamics. Navid holds a BSc in Naval Architecture and an MSc and PhD in Marine Structural Engineering.

EXECUTIVE SUMMARY

Commercial floating offshore wind projects will require the serial fabrication and assembly of large numbers of foundations. For steel substructures assembled near the deployment port, welding primary structural connections may constrain yard throughput because of the time required for welding, inspection and coating repair.

Bolted connections could shorten assembly times, but their suitability depends on retaining preload under cyclic loading generated by wind, waves, currents, turbine operation and platform motion in six degrees of freedom.

At connection level, these actions produce combined axial, shear, bending and torsional loads that vary in magnitude and direction. Conventional ring flanges are sensitive to preload variation, flange gaps and joint movement. Alternative connection systems may improve preload retention, but representative testing and offshore operating data remain limited.



THE SCALE UP CHALLENGE

Floating offshore wind is progressing from individual demonstrators towards projects requiring large numbers of foundations. Delivering these projects will depend not only on turbine and foundation design, but also on how efficiently foundations can be manufactured, transported and assembled. The scale up challenge is therefore not simply to design larger floating platforms. It is to produce foundations at a repeatable rate that supports the offshore installation program.

Welding remains the established method for joining steel floating foundations, with a long record in shipbuilding and offshore construction. Completing major structural welds at the assembly port, however, requires qualified personnel, controlled procedures, detailed inspection and coating repair. These activities increase the time each foundation occupies the assembly area.

WHY BOLTED CONNECTIONS?

Compared with completing large structural welds at the quayside, bolting could shorten assembly cycles, reduce yard occupancy and simplify some equipment and personnel requirements.

Bolting does not eliminate welding. Flanges and other connection components will normally still be welded to tubular members during fabrication. The difference is that these welds can be completed, inspected and coated in a controlled facility before final assembly.

At commercial scale, a floating wind farm could require hundreds of connections between primary structural members. Reducing the time required for each connection could reduce the number of assembly lines and help ports maintain the production rate required for offshore installation. Depending on the design, bolted assembly may also reduce coating repair and allow individual components to be replaced more readily.

Assembly time is not the only part of the business case. A bolted connection that reduces quayside work but requires increased offshore inspection, preload verification or component replacement could increase operational expenditure and offset the initial saving. Lower lifecycle cost therefore depends on both efficient assembly and reliable long term performance.



RELIABILITY CONSIDERATIONS: LOOSENING, CORROSION AND FATIGUE

Bolted joint performance depends on preload. Tightening stretches the bolt and compresses the connected components, creating the clamping force that holds the joint together.

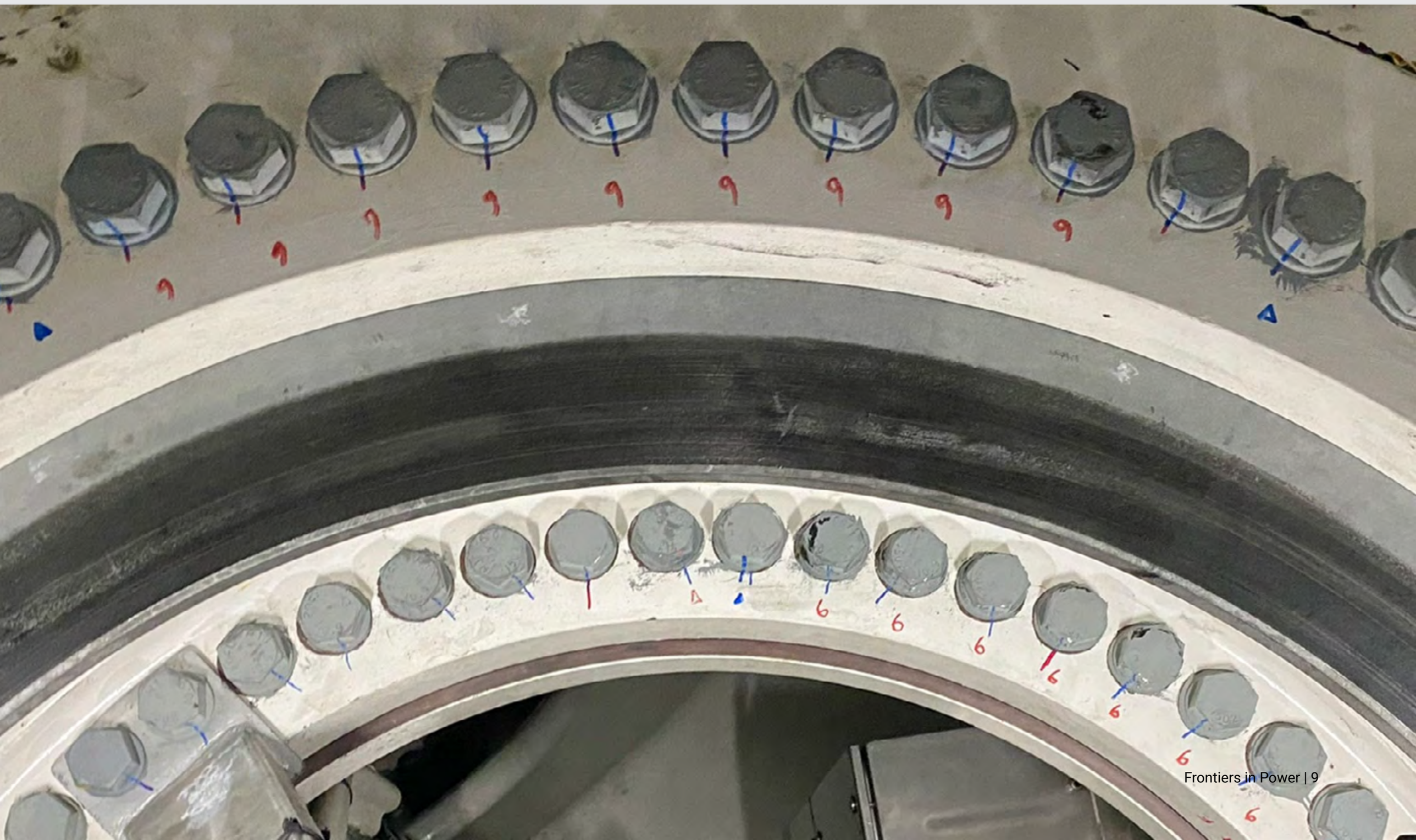
While sufficient preload is retained, a significant proportion of external loading can be transferred through compression and friction between the mating surfaces. If preload falls, local separation or interface movement can occur, increasing the load carried directly by the bolts.



Achieving consistent preload can be challenging on a single bolt and is even more challenging on large flanges, with large numbers of bolts. With torque-controlled tightening, only part of the applied torque stretches the bolt; much of it overcomes friction in the threads and beneath the nut. Variations in tool accuracy, lubrication, coating, surface condition and alignment can therefore produce different bolt tensions at the same nominal torque.

Tightening one bolt can also alter the preload in neighboring bolts through elastic interaction within the flange. Research indicates that a second tightening pass may improve preload consistency more effectively than changing the tightening sequence alone.

Achieving uniform preload across large-diameter flanges with many fasteners could be done using hydraulic tensioners. While tightening all bolts simultaneously would be the most effective way to minimize load deviations, the cost of implementing such a process across the entire equipment would be significant. On the other hand, a partial but evenly distributed tightening would minimize tools cost but expose to greater operation time and uneven load distribution.



Preload loss and rotational self-loosening are related but distinct. Preload can decrease because of settlement of contact surfaces, material relaxation, local deformation, temperature change, corrosion, misalignment or flange gaps. These mechanisms do not necessarily involve rotation of the nut. Rotational self-loosening occurs when relative movement within the joint overcomes friction and allows unintended rotation of the threaded components. The distinction is important because different mechanisms require different engineering controls.

Floating foundations experience cyclic loading from wind, waves, currents, turbine operation and platform inertia (see Figure 1). Motion in six degrees of freedom produces loads that change in magnitude and direction over millions of cycles.

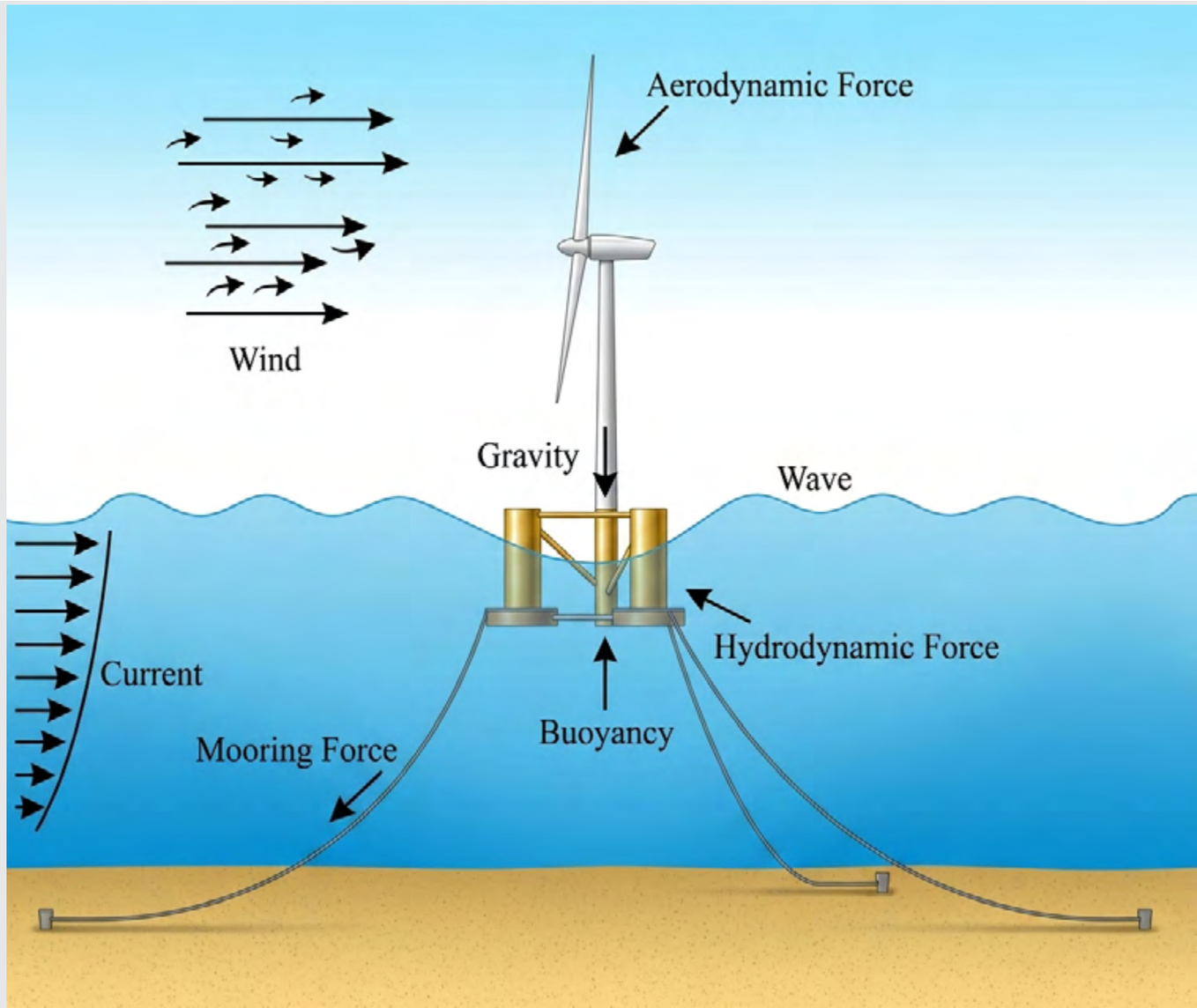


FIGURE 1:
Illustration of the main loading mechanisms acting on a floating offshore wind turbine.

If a joint opens or slips, cyclic bolt stresses increase, load distribution becomes less uniform, and the fatigue lifetime of the bolts will be reduced. Movement between the mating surfaces can cause fretting and initiate fatigue cracks. Failure of one bolt transfers additional load to neighboring bolts, and will inevitably lead to accelerating further damage. Loss of joint closure may also reduce the joint's water-sealing capability.

Corrosion can affect mechanical performance, damage threads and bearing surfaces, alter friction and reduce fatigue resistance. Coatings and corrosion-resistant materials can help but may also affect the relationship between applied torque and achieved preload. Preload, corrosion and fatigue must therefore be treated as interacting aspects of the connection design.

Corrosion could lead to preload loss, which in turn leads to increased fatigue, and could ultimately lead to catastrophic failure of the bolted flange. It is therefore crucial to minimize both corrosion and preload loss in bolted connections.

CONVENTIONAL RING FLANGES MAY NOT BE ENOUGH

Conventional L-type ring flanges have been used successfully in wind-turbine towers for many years (see Figure 2). This experience is valuable but does not demonstrate that the same design can be transferred directly to primary connections within floating foundations.

Tower-to-foundation flanges are generally horizontal; however, connections between primary members of a floating foundation may be vertically oriented or otherwise arranged within complex load paths, where gravity, buoyancy and platform motion can introduce substantial shear, bending and cyclic load interaction alongside axial loading.

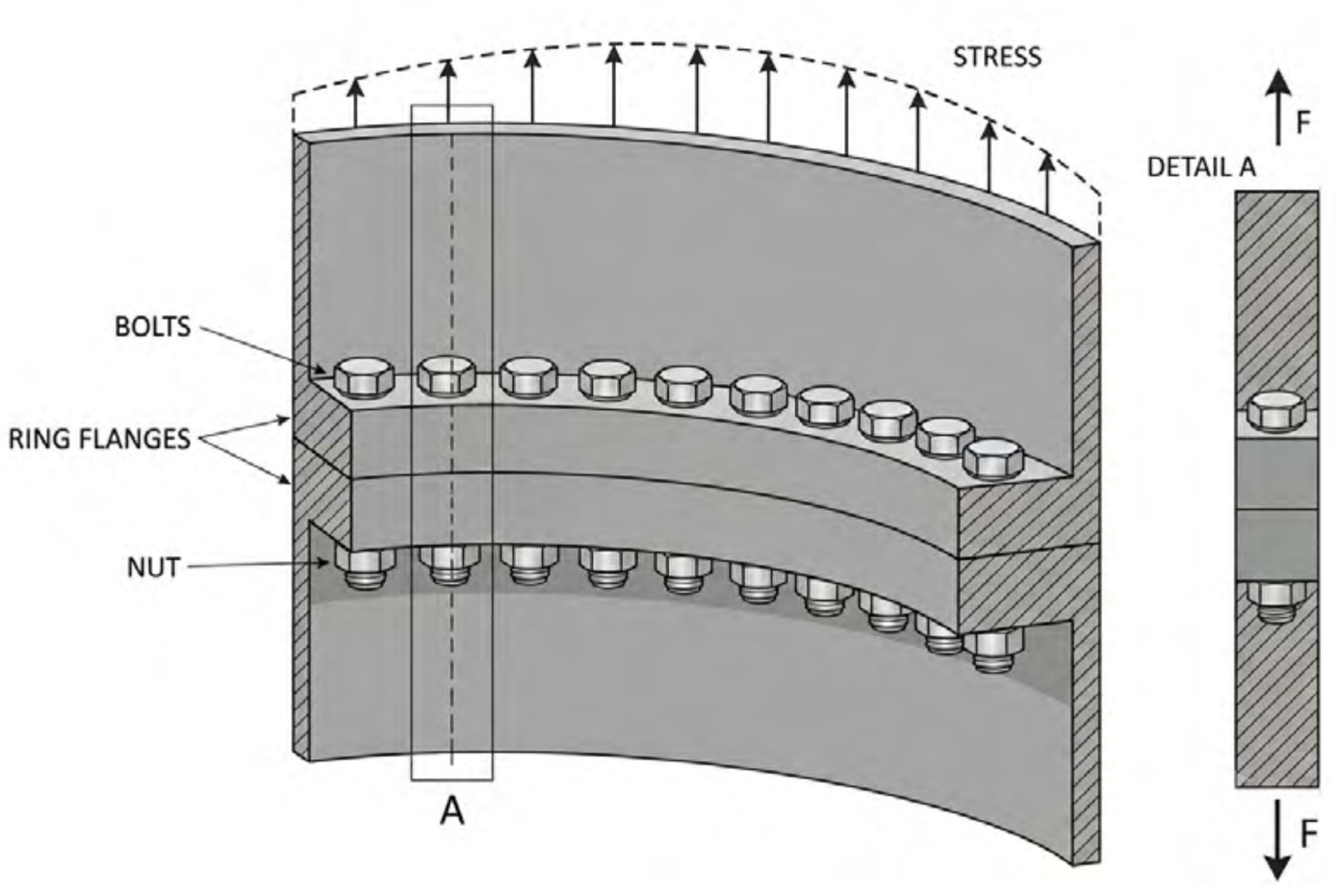


FIGURE 2:
Typical ring flange used in wind turbine towers

Ring-flange performance is sensitive to flatness and manufacturing tolerances. Gaps between mating faces can increase local flange bending and bolt stress.

Achieving uniform preload also becomes more difficult as the number and size of bolts increase. These issues are particularly significant where connections are subjected to substantial shear, complex cyclic loading and difficult offshore access. This does not mean ring flanges are inherently unreliable. Their suitability must be assessed for the specific connection orientation, load path and maintenance environment.

Alternative concepts seek to reduce fastener load variations. Some efforts have been made to develop flange connections using wedge-shaped connectors that draw tubular sections together through horizontal fasteners. Experimental and numerical studies showed promising preload retention and fatigue performance.

COMPACT FLANGE CONNECTION

Another concept is the Compact Flange Connection (CFC), which uses specially shaped flange faces and high initial preload to create compressive contact at the flange heel. During assembly, the initially warped flange faces are drawn together by the preload in the bolts, causing the flange plates to act as stiff springs (see Figure 3). This built-in reserve of elasticity helps the connection accommodate dynamic loading while limiting variations in bolt tension. In contrast to systems that rely on conical spring washers to provide additional elasticity at each fastener, the CFC integrates this function directly into the flange geometry itself.

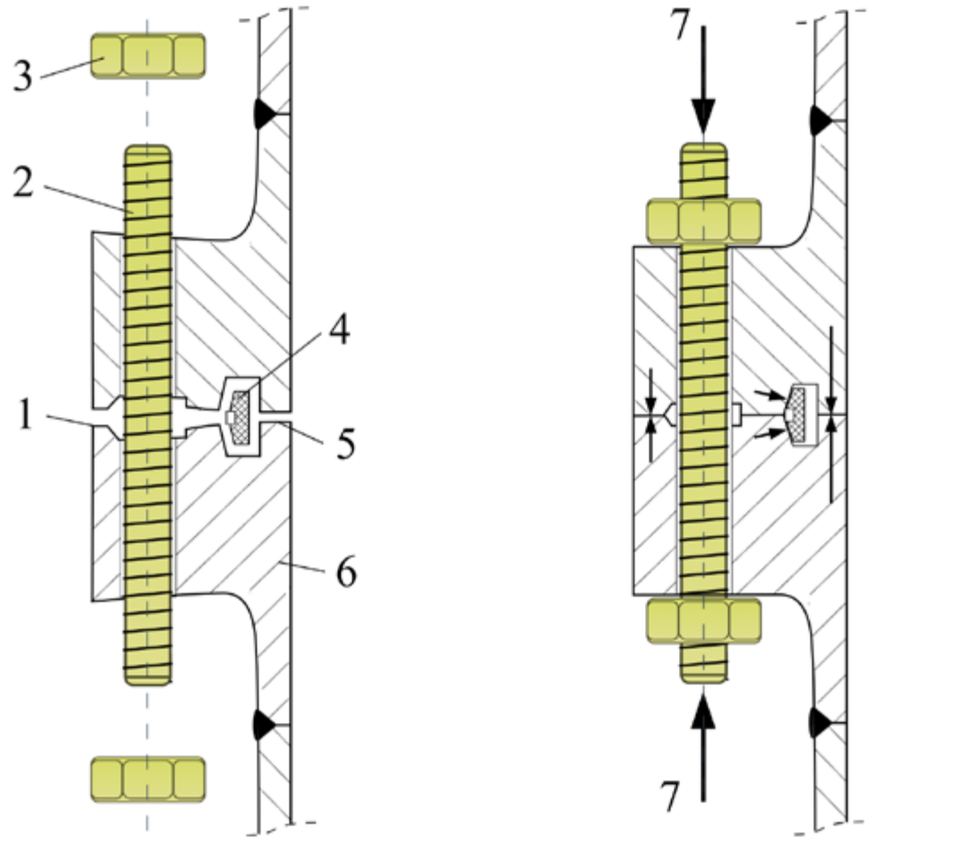
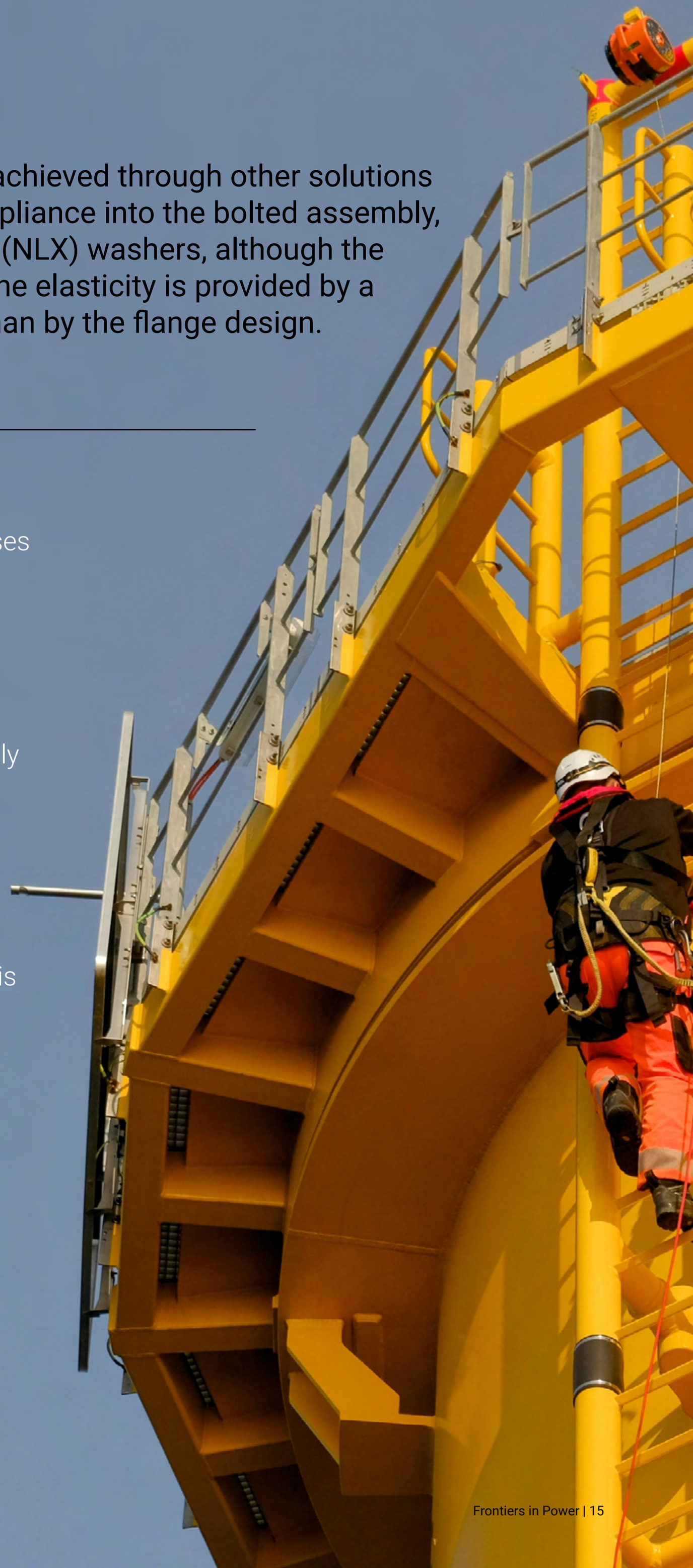


FIGURE 3:
Compact Flange Connection.
1: Wedge, 2: Stud, 3: Nut, 4: Seal ring, 5: Heel, 6: Weld neck flange, 7: Bolt clamping force.
The arrows indicate the bolt clamping forces applied to the flange and the resulting compressive forces on the flange plates and seal ring.

Similar benefits may also be achieved through other solutions that introduce additional compliance into the bolted assembly, such as Nord-Lock® X-series (NLX) washers, although the mechanism differs because the elasticity is provided by a separate component rather than by the flange design.

The objective is a relatively static joint in which external loading causes limited variation in bolt tension.

Compact flange technology has an established operating record in demanding offshore oil and gas applications, particularly pressure containing systems and dynamically loaded risers. However, floating wind structural members may be considerably larger and experience different load combinations.
The flange-to-tubular weld also remains a potential fatigue-critical location, even if bolt load variation is controlled.



ADDITIONAL MEASURES TO ADDRESS SPECIFIC FAILURE MECHANISMS

Where transverse movement creates a risk of rotational self-loosening, mechanical locking systems such as Nord-Lock® wedge-locking washers can help resist unintended rotation of the threaded components (see Figure 4). Moreover, supplementing bolted connections with such locking devices could reduce the need for periodic re-tightening or torque verification associated with self-loosening mechanisms, hence reducing operation and maintenance (O&M) requirements and improving the lifecycle economics of bolted connections.

FIGURE 4:
Example of a wedge-locking washer system used to mitigate rotational self-loosening in bolted joints.



However, when preload loss is caused predominantly by settlement, material relaxation, corrosion, or flange deformation, rather than bolt rotation, locking washers alone may not fully address the underlying issue. They do not replace the need for correct preload, adequate joint stiffness, flatness control, fatigue verification or corrosion protection. Any locking system should therefore be selected as part of the overall connection design rather than as a standalone solution.



REMAINING CHALLENGES AND GAPS

Before commercial adoption, bolted connections for floating foundations need to be tested and adapted to withstand the combined loading conditions experienced during operation, where axial, shear, bending, and torsional loads act together. Particular attention should be given to vertically mounted flange connections, where shear forces can be significant, and to large-diameter fasteners.

The flange-to-tubular welds must also be assessed. A connection may limit bolt-load fluctuations but transfer fatigue demand to the welded transition, particularly where fabrication imperfections are present. Even where bolt load variation is successfully minimized, fatigue damage may migrate to the flange-to-tubular transition, weld toes or other local stress concentrations within the flange geometry.

Manufacturing tolerances present another practical challenge. Floating foundation components can be tens of meters long, and a commercial scale project may involve hundreds of connections and thousands of bolt holes. Even small geometric imperfections can lead to uneven contact pressures and load distribution, resulting in higher bolt stresses than predicted by idealized analyses. Tolerances must therefore be carefully controlled to ensure efficient assembly and alignment while preventing gaps or relative movement that could compromise fatigue performance.

Inspection requirements should be considered during design. Manually checking many bolts inside confined areas of a moving offshore structure would be costly and may expose technicians to additional risk. Remote monitoring could identify changes in preload or connection behavior, but current methods require further full-scale validation.

Existing standards guide preload, corrosion and fatigue, but much of the underlying experience comes from bottom-fixed wind or other offshore sectors.

Full-scale demonstrators must show that these connections can be manufactured, installed, inspected and operated reliably throughout their intended service life.

CONCLUSION

Floating offshore wind will require a step change in manufacturing and assembly efficiency if the industry is to deploy projects at the scale required over the coming decades. In this context, bolted assembly offers a potentially attractive route to industrializing foundation production by shifting more fabrication, inspection and coating activities into controlled manufacturing facilities and reducing the amount of work undertaken at the assembly port. However, the feasibility of bolted assembly for primary connections in floating offshore foundations cannot be assessed solely on the basis of assembly speed. Long term performance depends on maintaining sufficient preload under combined cyclic axial, shear, bending and torsional loading while also managing corrosion, fatigue and manufacturing tolerances. The challenge is not simply to prevent bolt loosening, but to ensure reliable load transfer throughout the design life of the structure.



Experience from wind-turbine towers, offshore oil and gas applications and other industries provides valuable insights, but it does not yet fully demonstrate the suitability of existing bolted connection concepts for large floating offshore wind foundations. In particular, preload retention, joint behavior under multidirectional loading, fatigue performance of flange-to-tubular transitions, and practical inspection requirements all require further validation through representative testing and full-scale demonstration projects.

Bolted connections should therefore be viewed not as a replacement for welding, but as an alternative assembly philosophy with the potential to improve project delivery and reduce lifecycle costs.

Whether that potential can be realized will depend on proving that faster assembly can be achieved without introducing unacceptable reliability, inspection or maintenance burdens offshore. If these challenges can be addressed, bolted assembly could become an important enabler of commercial-scale floating offshore wind deployment.



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Nord-Lock® wedge-locking washers use tension instead of friction to secure bolted joints - maintaining preload even under dynamic loads.

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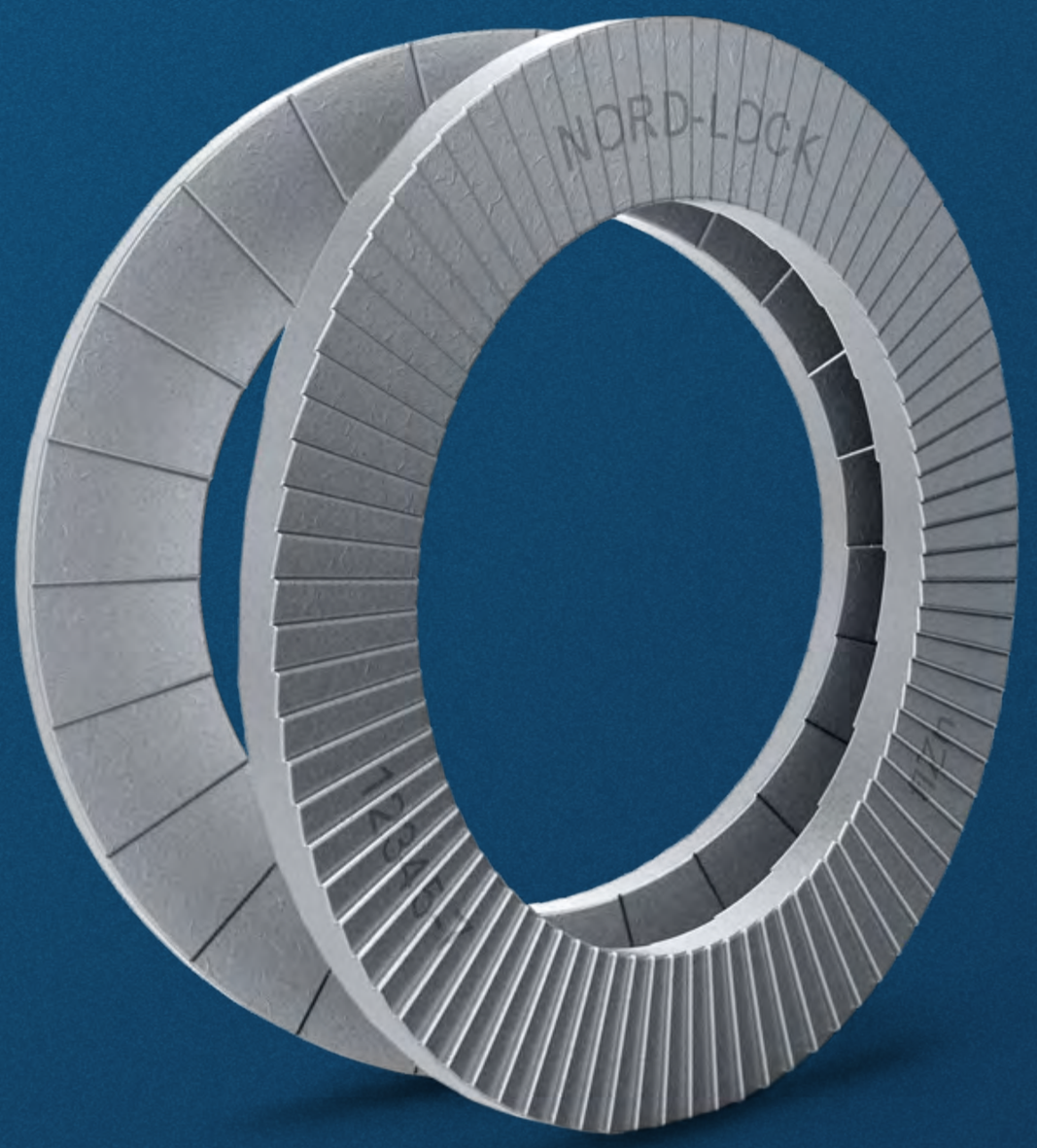
Nord-Lock® steel washers undergo a minimum of 1,000 hours in salt spray test in accordance with ISO 9227.

Prevents Vibration-Induced Loosening:

All Nord-Lock® washers are designed to use physical geometry to create a mechanical locking effect on bolted joints, preventing them from loosening in high vibration environments.

Easy to Assemble:

Nord-Lock® washers are designed as a pair and come glued together for easy and precise installation. The system does not require modifications to the bolting elements.



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ANALYSIS OF LEGACY VS EMERGING SURFACE TREATMENTS FOR IMPROVING WEAR RESISTANCE IN HYDRO TURBINES

RODOLPHO FERNANDO VÁZ, PH.D.

Rodolpho Fernando Váz is a Professor at Department of Materials Sciences and Chemistry Physics at Universitat de Barcelona. Dr. Vaz is a Mechanical Engineer with a master's and a doctorate degree in wear-resistant materials. Dr. Vaz participated as a researcher in many R&D projects with companies to improve reliability of hydro-turbines. Nowadays, Dr. Vaz develops new metallic alloys for cold spray deposition for wear-resistant coatings.

CAVITATION RISKS IN THE ERA OF FREQUENT START-STOP CYCLES

Hydropower is a cornerstone of the energy transition because it provides reliable electricity at both small and large scales while helping compensate for the intermittency of renewable sources such as wind and solar. The energy transition, however, is also challenging engineers to develop hydropower projects under increasingly diverse operating and environmental conditions. Regions that were previously considered unsuitable for hydropower are now being considered for new applications.



A representative example is the pumped-storage hydropower system in Hatta, Dubai, interconnecting lower and upper reservoirs to generate electricity during periods of peak demand and pump water uphill during off-peak periods. Several countries have invested in small hydropower plants (<25 MW), including China, India, Brazil, and Uzbekistan, particularly to provide electricity to rural areas and support agricultural activities. In the United States and the European Union, significant investments have also been directed toward modernizing aging water infrastructure and supporting small-scale hydropower to strengthen the grid and increase renewable-energy utilization.

These developments expose hydro-turbine components to increasingly demanding and variable service conditions. Water quality and the operating regime may expose turbines simultaneously to hard-particle impacts, cyclic loading, and fluctuations in hydraulic pressure, leading to corrosion, erosion, abrasion, cavitation, and fatigue cracking.

Consequently, hydro-turbines experience material loss, reduced hydraulic efficiency, and, in severe cases, catastrophic failure.

Cavitation and vibration-related damage can become particularly severe during transient operating conditions, especially during turbine start-up and shutdown. This is particularly relevant to hydropower plants developed to support the energy transition, where turbines may operate for only a few hours per day and consequently experience a greater number of start-stop cycles, increasing their exposure to damaging transient conditions and creating a stronger demand for more damage-resistant materials, surface treatments, and component designs.

CONVENTIONAL ENGINEERING SOLUTIONS FOR CAVITATION AND VIBRATION-RELATED DAMAGES



Casting, Welding, and Heat Treatments:

Historically, hydro-turbine runners were manufactured primarily from cast C-steel or cast iron because of their relatively low cost, material availability, and established processing routes. Advances in metallurgy, materials science, and manufacturing—particularly welding and heat-treatment technologies—enabled martensitic stainless steels–with ASTM A743 CA6NM (shortened CA6NM) being a prominent example in the 1960s–to progressively replace these materials and welding or joining runner parts instead of casting a single-part one.

CNC Machining:

More recently, CNC machining has increasingly been employed to reduce microstructural heterogeneity and other detrimental effects associated with casting and welding while providing tighter dimensional tolerances to improve geometric accuracy and hydraulic performance. For a casting/welding assembly configuration, I faced the challenge of replacing a fractured blade of an old small Francis-type runner. The runner was composed of C-steel blades and a gray cast iron cone. Due to its low weldability, the technical solution was to mechanically add steel inserts into the cast iron and weld the new blade to these inserts. The runner returned to operation after dynamic balancing and is still running without issues.



Computational Fluid Dynamics:

The evolution of computational modeling has provided another important engineering tool. CFD, for example, enables engineering teams to optimize water-flow behavior within hydro-turbines, contributing to improved hydraulic performance and reduced cavitation damage . Furthermore, CFD can also support the repowering and modernization of existing hydro-turbines by identifying limitations in legacy hydraulic designs and enabling modifications that improve runner reliability and performance. This is particularly relevant to the energy transition, where modernization can increase the performance of aging small hydropower plants without necessarily requiring entirely new infrastructure. I participated in the modernization of the Brazilian Foz Do Areia power plant, where CFD tools were used to change the turbine configuration, optimize the guide vanes profile, and design a new 6m diameter Francis-type runner, reducing the number of blades from 16 to 15 and using CA6NM instead of carbon-steel. Since then, only minimal wear repair services have been required.



Surface Treatments and Protective Coatings:

On the other hand, surface engineering provides an additional strategy for mitigating degradation. Erosion, abrasion, and corrosion can be addressed through surface treatments and protective coatings for runners, extending component lifetime and improving equipment reliability. Outward surface treatments involve depositing a different material onto the substrate: coatings, which have received greater industrial attention and are now among the most established surface-engineering solutions for hydropower applications.

RECENT FIELD SUCCESSES OF LEGACY SURFACE TREATMENTS AND COATINGS



Cermet Coatings:

Cermet coatings combine a hard ceramic phase—typically WC or Cr_3C_2—with a metallic binder. The hard phase provides high hardness and wear resistance, while the binder contributes toughness and helps preserve coating integrity under mechanical loading . High-Velocity Oxy-Fuel (HVOF) spraying is one of the most effective technologies for depositing carbide-based coatings. It produces dense coatings with strong substrate adhesion and thickness reaching the mm-scale. For field applications and in-situ repairs, however, lower-cost and more portable technologies such as arc- and flame-spraying remain attractive alternatives.

Welding-based deposition:

Welding-based deposition is also widely used to restore and protect hydro-turbines. I managed a team responsible for repairing a large volume of cavitation-damaged material on the Brazilian Foz Do Areia power plant Francis-type runners by depositing stainless steel and subsequently several millimeters of a Co-rich alloy–Cavitalloy– to improve wear resistance and extend turbine lifetime . It reduced the cavitation wear rate and, after 4,000h of operation, this runner needed only 45kg of welded material for restoration instead of hundreds of kilograms required for previous services.

CA6NM microstructure changes during arc-welding and high-temperature exposure, forming untempered martensite–a brittle phase. Laser cladding has emerged due to its lower dilution and reduced tensile residual stresses. It has therefore been increasingly investigated and implemented for repairing worn regions on small runners and protecting new components , as illustrated in Figure1 for a CA6NM Francis-type runner repaired with 410 NiMo steel. This was a spare part that after repair was sent to the client. The feedback was that the runner was installed months later and was running without any issue, especially because the base metal and deposited materials have similar properties and wear performance. In this case, only a volumetric repair was required and no wear improvement with hard coating or high-wear-resistant material deposit was demanded.

For corrosion protection, Al- and Zn-based coatings and polyurethane paints provide effective and relatively low-cost protection . These systems are attractive for large static components such as bulb-type turbine scroll cases and draft tubes. Their principal limitation is their relatively low resistance to severe silt erosion and impact from foreign debris.

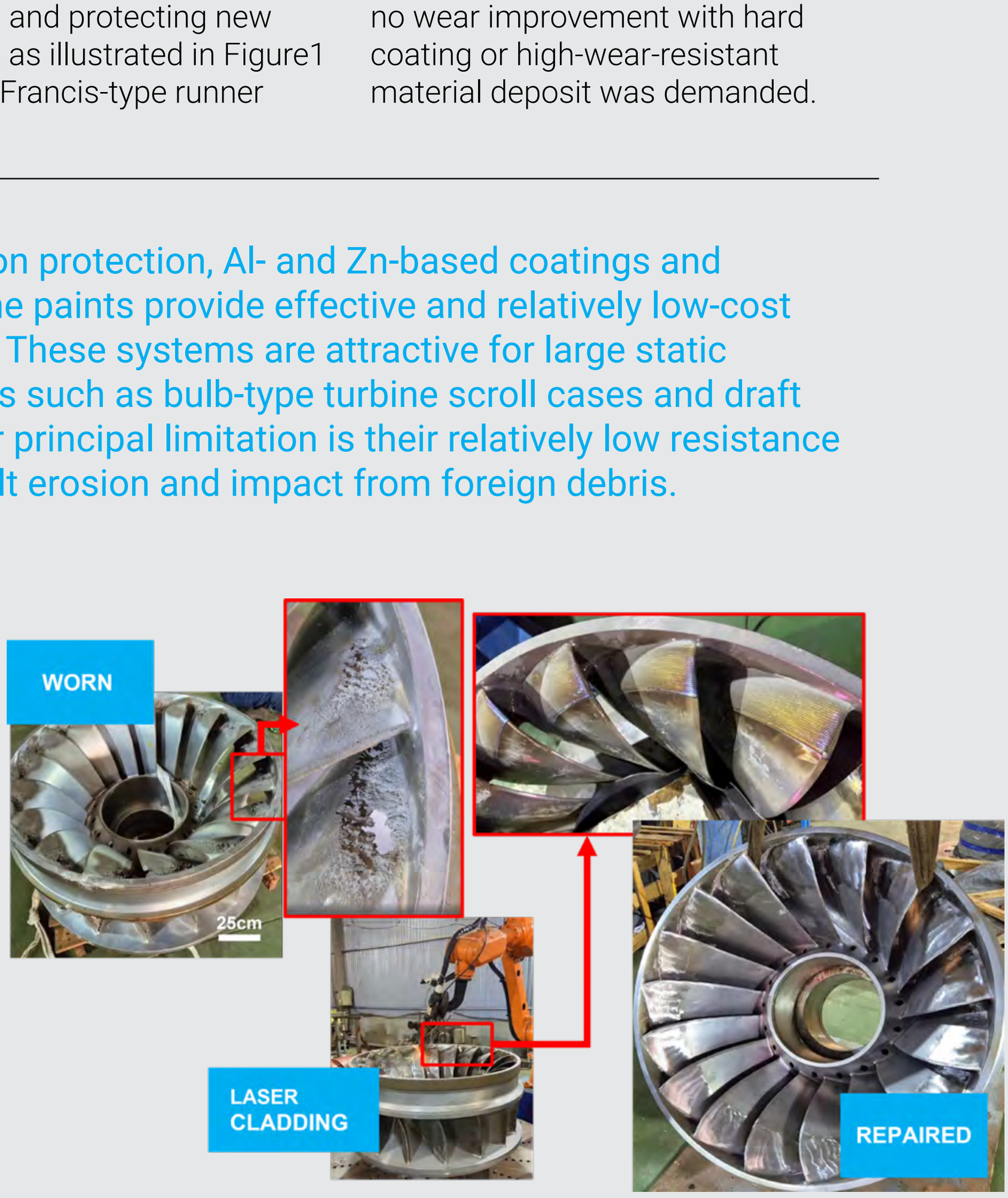


FIGURE 1:
Francis-type runner repaired by laser cladding

EMERGING SOLUTIONS IN EXPERIMENTAL PHASE AND THEIR CHALLENGES

A key takeaway for next-generation hydro turbines is that degradation mechanisms rarely act alone—cavitation, silt erosion, corrosion, and fatigue interact synergistically. Because of this, optimizing a runner for just one mechanism doesn't guarantee long-term reliability. For example, a runner shape engineered purely to minimize cavitation can still fail prematurely under an unexpected synergy of erosion, corrosion, and fatigue. Water quality plays a major role here: testing showed that altering water characteristics (like lowering surface tension) directly reduced the cavitation wear rate on WC-Co coatings . In practical terms, testing with real river-water chemistry gives a much more accurate prediction of field wear, supporting material selection for manufacturing a new component or repairing an old one.



New Coating Architecture or Coating Systems:

To tackle these combined threats, one smart strategy is building multi-property coating systems where different layers handle different stresses. It is possible by adjusting deposition techniques, parameters, or alloy compositions as the coating builds up. Functionally Graded Coatings (FGCs) take this a step further by smoothly transitioning composition or hard grains content through the coating thickness. FGCs smooth out internal stress distribution and boost fracture toughness. This strategy can be implemented by updating the deposition strategies and toolpaths.

For cermets, adjusting the binder content and composition or hard grain size across different layers improves particle cohesion and toughness while keeping surface abrasion resistance high. Using this layered approach is less costly and safeguards supply chains—reserving expensive or critical materials like WC-Co strictly for the high-wear outer surface, while using standard, lower-cost alloys for the underlying layers.

High-entropy Alloys:

High-entropy alloys (HEAs) represent another exciting material class. By mixing multiple principal elements into simple solid solutions, HEAs offer an outstanding balance of hardness, deformation capacity, corrosion resistance, and alloy flexibility . However, two major hurdles stand between HEAs and everyday shop floor use:

Finding the right recipe: Narrow down the best HEA formulas for hydro applications, a process where machine learning and artificial intelligence tools will be crucial to speed up screening.

Realistic benchmarking: Beating bare stainless steel isn't enough to justify the cost. HEAs must prove they can outperform proven industrial solutions—like HVOF-sprayed cermets and heavy-duty weld overlays—before justifying their adopting on a large scale.





Fe-based amorphous coatings–or metallic-glasses:

Fe-based amorphous coatings (or metallic glasses) are another promising option for components exposed to aggressive erosion, corrosion, and cavitation. In fact, Fe-based alloy coatings have already shown lower erosion-corrosion rates than standard CA6NM . However, getting consistent performance comes down to chemistry and process control. E.g., controlled heat treatment (devitrification) boosts matrix hardness, while adding Mo stabilizes the amorphous phase and improves corrosion resistance. The catch? Field performance depends on balancing act: stable passive film, high toughness, strong inter-particle cohesion, and solid crack resistance. Tuning an Fe-based amorphous alloy to deliver all of these at once remains a real materials engineering challenge.

To test this in the field, I applied an Fe-based alloy using arc-spraying to perform an in-situ repair on a large CA6NM Francis runner at the Ney Amintas de Barros plant in Brazil.

The field repair process followed four standard maintenance steps:

- Mapping and identifying damaged zones.
- Grinding and grit blasting for surface preparation.
- Arc-spraying the Fe-based coating up to 2 mm thick.
- Final surface grinding and polishing (Figure 2)

As shown in Figure 2, the cross-section exhibits the typical microstructure of thermal spraying—a mix of metallic splats, oxide layers, and porosity.

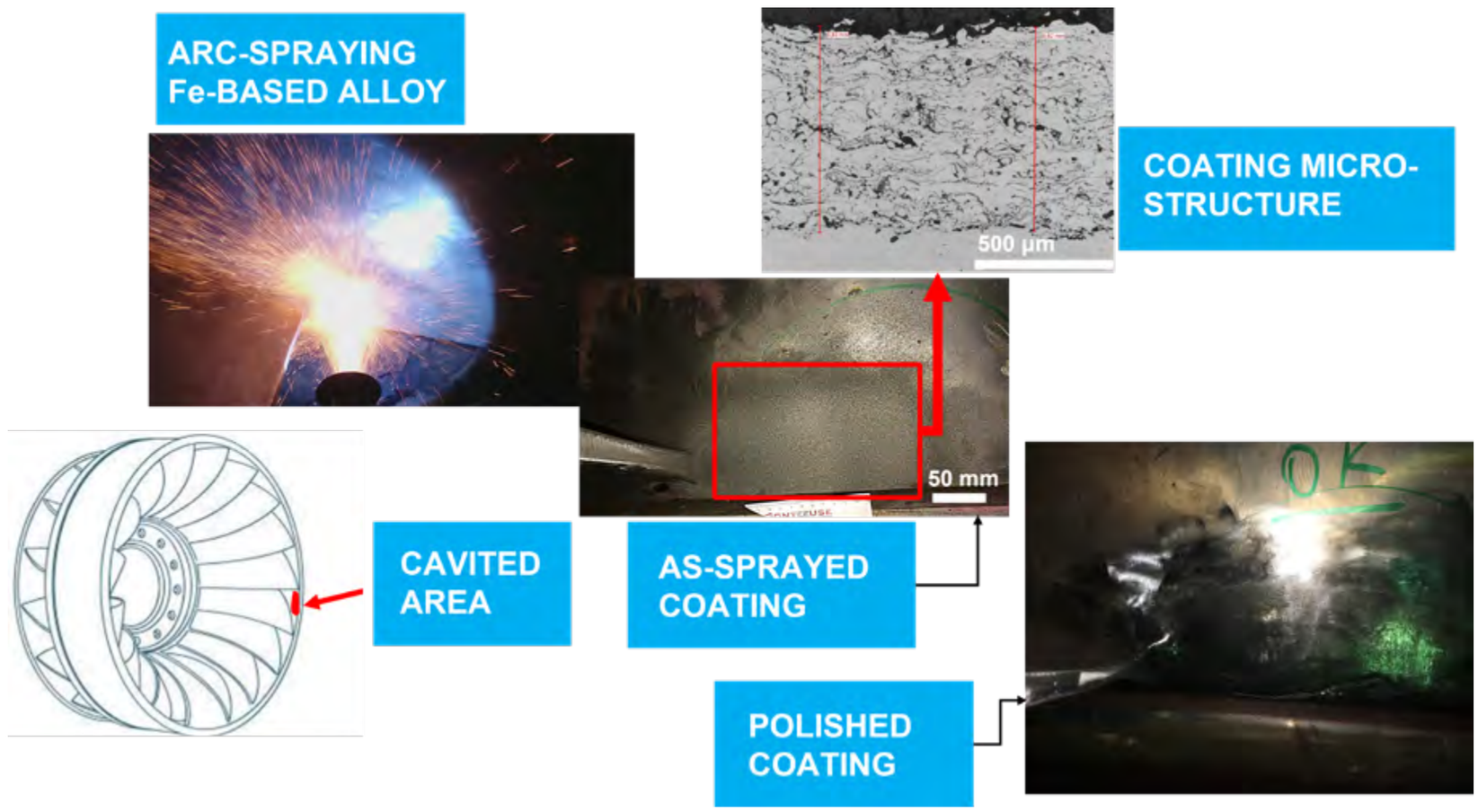


FIGURE 2: Francis-type runner repaired by arc-spraying with Fe-based alloy.

Inspection after 2,000 operating hours showed the Fe-based coating outperformed bare CA6NM, which had developed a noticeably rougher, worn surface.

However, by 4,000 hours, the coating started spalling in areas where it was applied too thin. With this, it is clear that a great alloy and spray process aren't enough on their own. To reach true industrial readiness, it's necessary to design proper coating architecture—especially establishing strict minimum thickness guidelines across the entire blade geometry.

OUTLOOK

Relying exclusively on legacy manufacturing and repair methods is no longer sufficient to meet the operational demands imposed on hydropower assets by the energy transition—particularly regarding unpredictable synergistic degradation mechanisms (erosion, cavitation, abrasion, and corrosion).

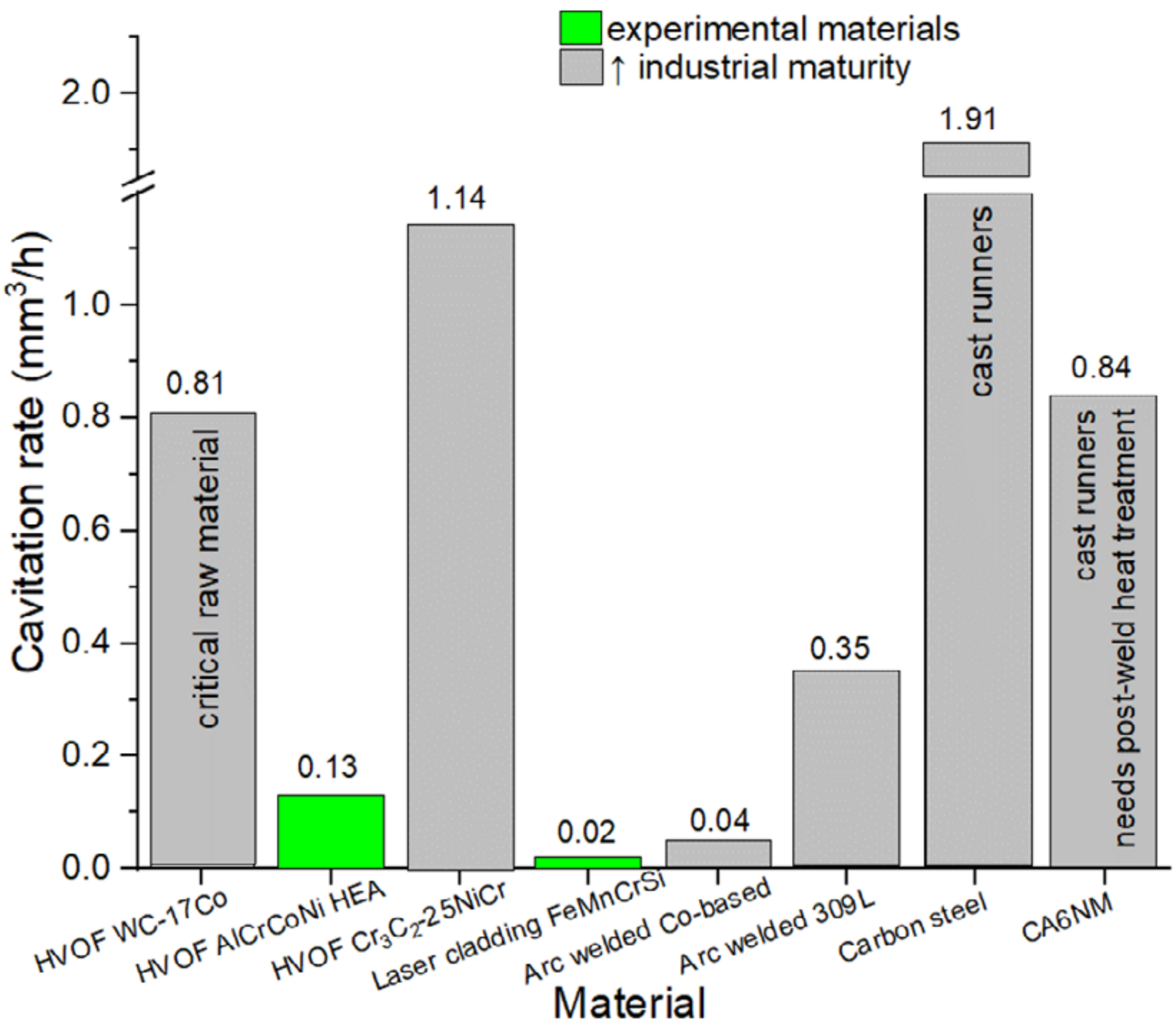
Advanced surface engineering, novel alloy compositions, and tailored coating architectures are essential to ensure long-term turbine reliability under flexible operation.



As illustrated in Figure 3, emerging laboratory-scale surface treatments demonstrate significantly lower cavitation erosion rates than conventional alloys. Several of these material systems are advancing along the Technology Readiness Level (TRL) scale, with select HEA coatings reaching TRL 6 (prototype demonstration in relevant operational environments).

Importantly, many of the thermal deposition techniques required to apply these advanced formulations—such as laser cladding, arc spraying, and HVOF—are already industrially mature and widely deployed in manufacturing and maintenance shops.

FIGURE 3:
Cavitation resistance of mature and experimental materials



Consequently, deploying next-generation surface solutions relies primarily on optimizing process parameters, feedstocks, and spatial deposition strategies rather than developing entirely new machinery.

Functionally Graded Coatings (FGCs) exemplify this advantage: by dynamically adjusting powder feed ratios or deposition parameters during processing, tailored microstructures and property gradients can be synthesized using existing machinery.

From an industrial engineering perspective, novel materials must demonstrate reproducible performance under real-world conditions and be supported by a robust, scalable supply chain. In this regard, FGCs are closest to immediate industrial implementation because they utilize existing commercial feedstocks. Conversely, HEAs and metallic glasses require further fundamental characterization, standardized qualification protocols, and supply-chain maturation before widespread commercial adoption can be realized.

In conclusion, materials research and development is more critical to hydropower reliability today than at any point in recent history, ensuring that hydro infrastructure can adapt to the rigorous demands of the global energy transition.



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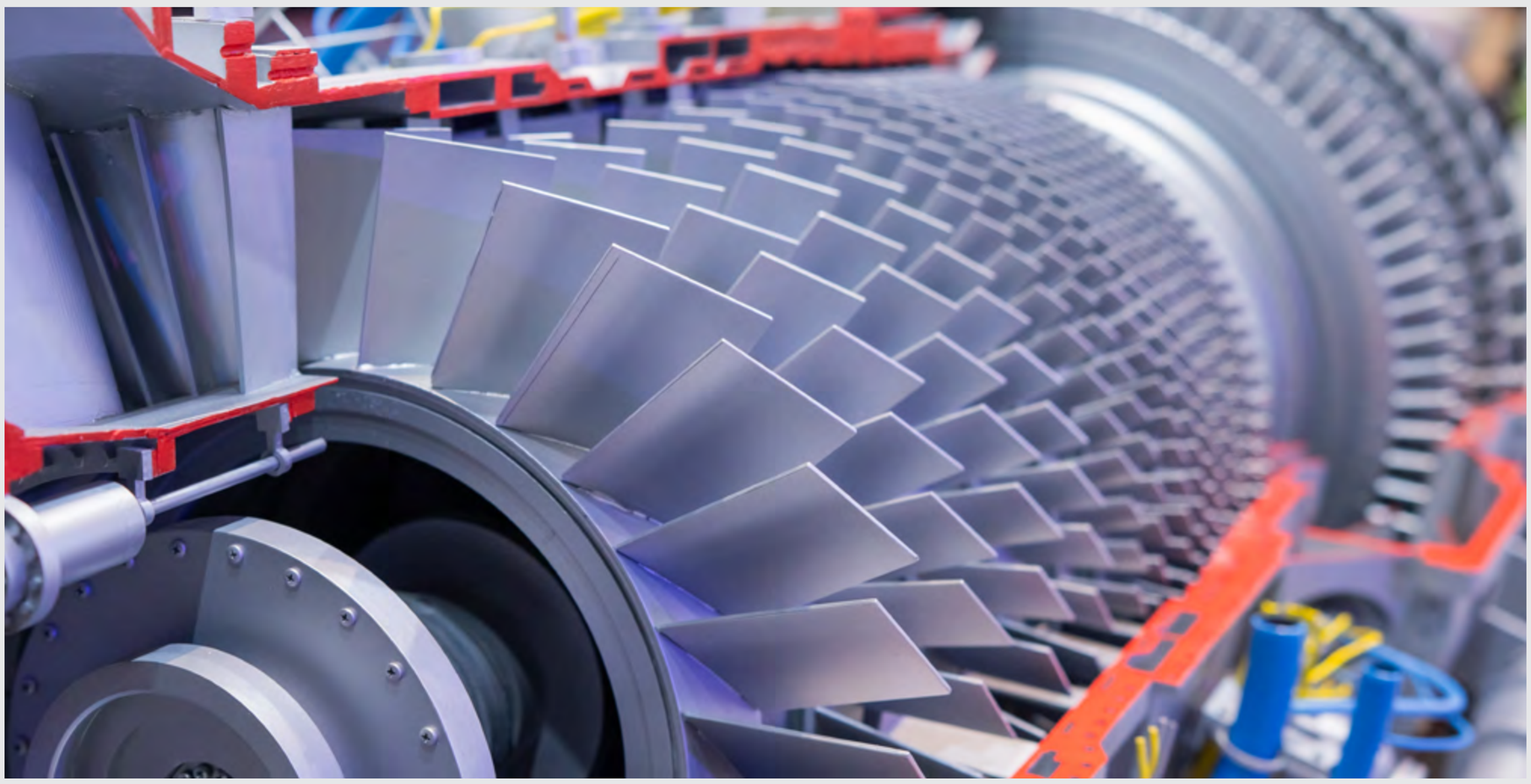
AN INTEGRATED APPROACH TO PREDICTING STRUCTURAL DAMPING OF 3D PRINTED COMPONENTS IN HYDROGEN-READY GAS TURBINES

ENG. ALESSIO CASCINO, PH.D.

Dr. Alessio Cascino is a Post-Doctoral Researcher at the University of Florence, Italy. He brings over five years of international R&D experience, leading and managing technical contributions for major industrial corporations across the energy, automotive, and railway transportation sectors. Author of 25+ peer-reviewed publications, his work focuses on integrating advanced simulation, physical design, and emerging technologies to drive engineering performance, project execution, and sustainable innovation.

INTRODUCTION

The global shift toward zero-emission power generation is forcing gas turbine technology through one of its most radical evolutions in decades. As operators and original equipment manufacturers (OEMs) move from natural gas to high-hydrogen fuel blends, and ultimately 100% hydrogen, the operating environment inside the combustion chamber changes radically.



Hydrogen burns faster, at higher temperatures, and with significantly higher flame speeds compared to traditional fuels. These combustion characteristics trigger intense thermoacoustic instabilities, severe dynamic pressure oscillations, and unprecedented thermal stresses on critical hot-gas path components. Furthermore, harsh thermochemical phenomena associated with hydrogen combustion can accelerate material degradation and reduce overall component performance over time.

From an operational standpoint, these combined effects introduce major challenges regarding dynamic stability and machine vibration. Uncontrolled dynamic behavior not only threatens operational continuity, but it can also increase noise pollution and environmental exposure in the surrounding area.

For engineering and maintenance teams, this transition represents a major asset-reliability challenge. Rather than rendering existing equipment obsolete overnight, it has driven the power generation industry into an active phase of rapid adaptation and redesign. In this evolving landscape, Additive Manufacturing (AM) is playing a pivotal role, enabling the innovation and structural optimization required to meet these demanding new combustion environments.



ADDITIVE MANUFACTURING AND THE CHALLENGE OF STRUCTURAL DAMPING

In order to mitigate combustion instabilities and handle extreme thermal loads, gas turbine design increasingly leverages Additive Manufacturing (AM). Traditional casting and machining impose severe geometric constraints, whereas industrial AM overcomes these boundaries to enable highly intricate, monolithic assemblies tailored for hydrogen-ready architectures. This design freedom enables the direct integration of micro-swirlers, complex fuel manifolds, advanced cooling channels, and lightweight structural brackets into single-build components, such as burners, turbine blades, and combustor liners, reducing assembly complexity and eliminating potential leak paths. However, deploying AM components into high-vibration environments introduces complex dynamic hurdles.

Structural damping serves as the primary line of defense against High-Cycle Fatigue (HCF) failure when thermoacoustic oscillations excite the structure.

Unlike conventional forged or cast parts with uniform properties, AM components exhibit complex energy dissipation driven by specific internal mechanisms: microstructural anisotropy and grain morphology caused by layer deposition, surface roughness causing internal friction in hollow passages, process induced micro-porosity altering local stress distributions, and high residual stress states from thermal build gradients. Overestimating this damping capacity leads to operational dynamic stresses exceeding design limits and triggering premature fatigue, while underestimating it causes unnecessary overengineering.

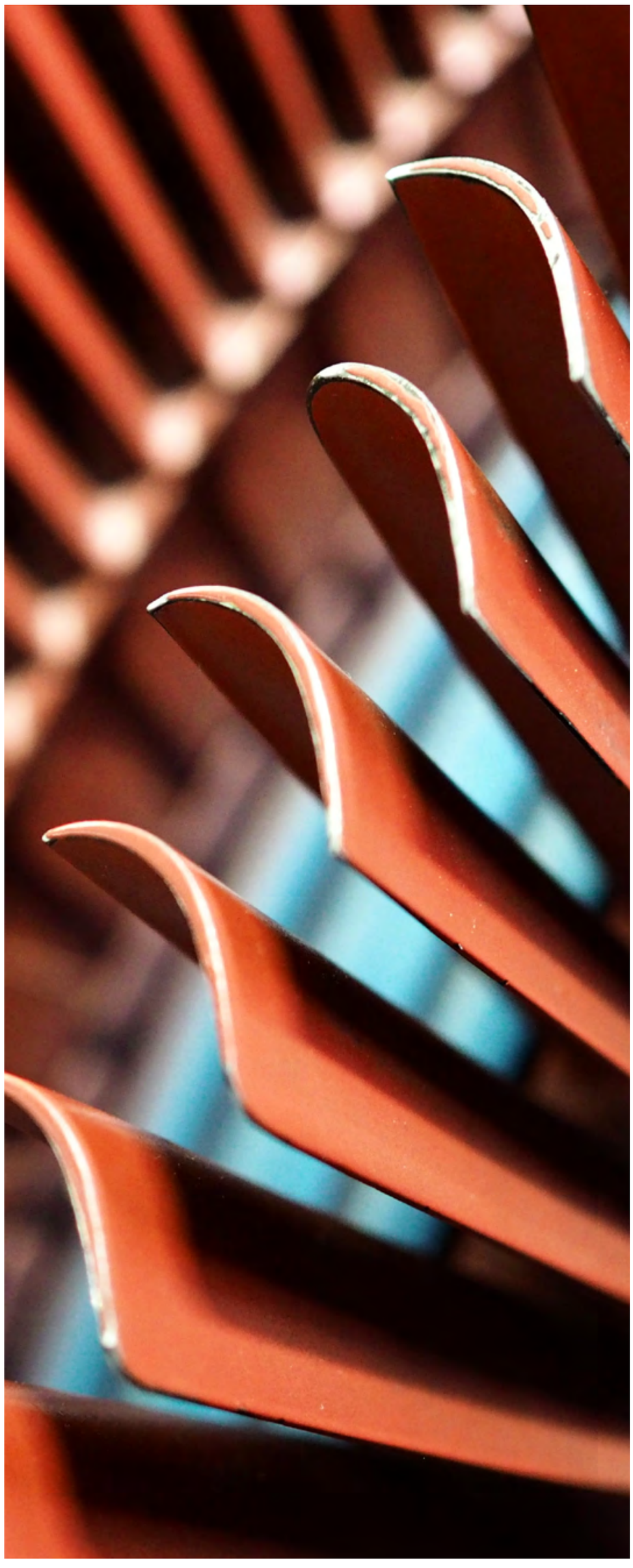
Accurately characterizing structural damping is therefore an absolute necessity to predict resonance, optimize geometries, and ensure the long-term reliability of hydrogen-ready assets.

BRIDGING SIMULATION AND REALITY: A PRACTICAL METHODOLOGY FOR AM COMPONENTS

Predicting structural damping in complex additive-manufactured geometries requires bridging the gap between numerical simulation and target empirical testing. While standard Finite Element Analysis (FEA) is essential for mapping mode shapes during early design phases, commercial solvers often rely on simplified damping formulations, such as uniform Rayleigh damping, that fail for lowmass, high-stiffness prototypal components. These models cannot natively capture the localized energy dissipation driven by microstructural anisotropy, process-induced porosity, or complex internal passages. Conversely, relying solely on empirical testing during prototype development leaves blind spots regarding internal dynamic stress distribution under operational loads.

With the aim of overcoming these constraints, an effective strategy relies on an integrated numerical-experimental workflow: using impulse excitation testing (ping test) on physical prototypes to iteratively calibrate a high-fidelity finite element model via the Half-Power Bandwidth Method (HBM).

BOUNDARY CONDITION SELECTION: EVALUATING SYSTEM DYNAMICS FOR RELIABLE TESTING



Selecting the appropriate boundary condition is a critical first step during early-stage dynamic characterization. Whether an experimental measurement yields reliable, component-specific data depends entirely on how the mass, inertia, and stiffness of the tested part interact with the surrounding environment. To balance intrinsic material identification with operational validation, testing must be structured across two distinct boundary setups:

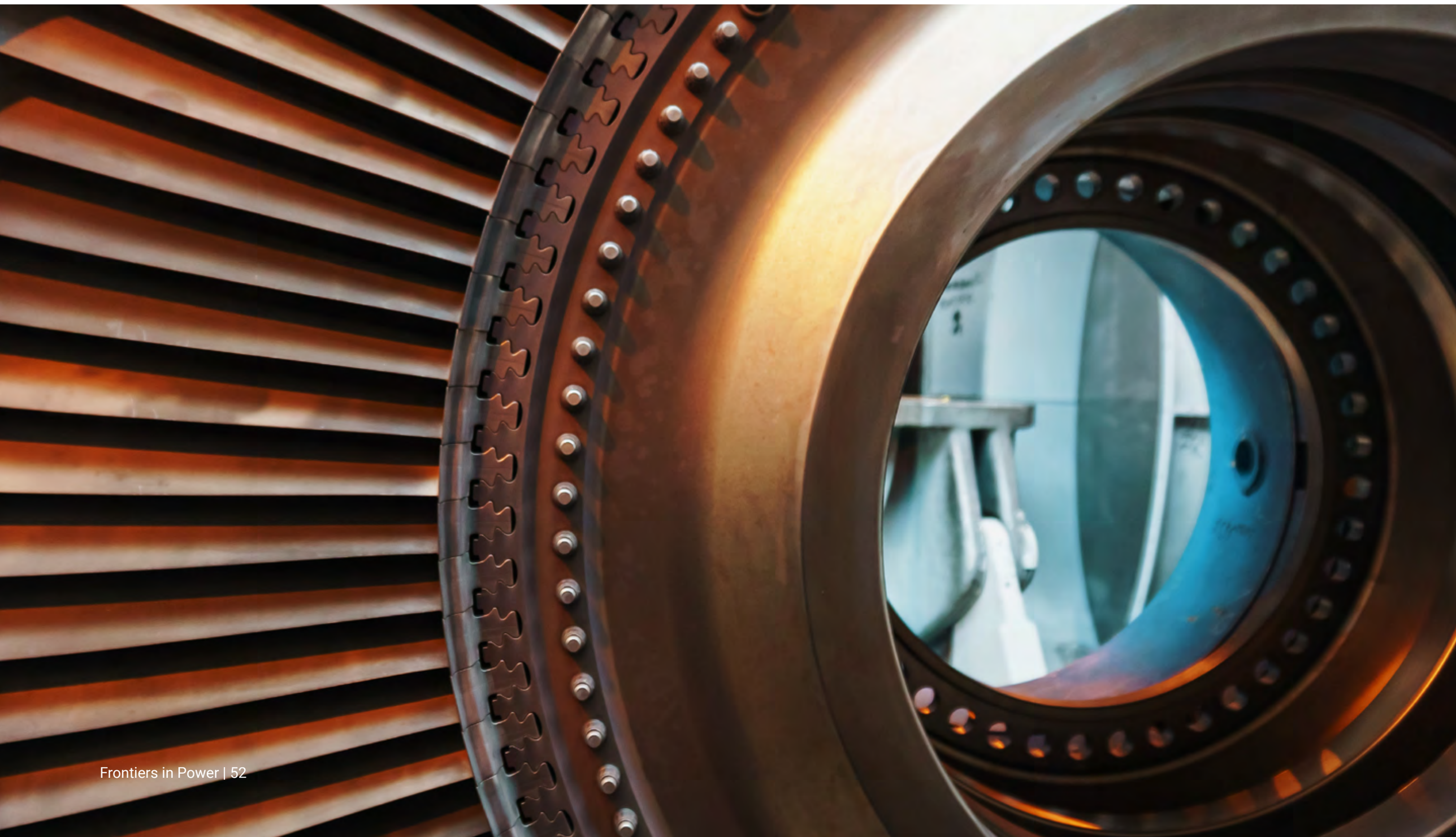


Starting with the free-free configuration as a baseline:

In any dynamic characterization workflow, testing is always performed first in a free-free (suspended) setup. By uncoupling the component from external fixtures, this setup eliminates joint friction, micro-slip, and fixture inertia. It isolates the intrinsic natural frequencies and baseline structural damping of the printed alloy, providing the clean, reproducible empirical baseline required to calibrate FEA material models before introducing complex mechanical interfaces.

Evaluating the constrained configuration:

Once the intrinsic dynamics are established, the component is evaluated in its constrained assembly (e.g., fastened to a test rig or combustion vessel). However, engineering teams must carefully evaluate the relative dynamic scales of the system. If a lightweight, high-stiffness AM component is fastened to a massive structural assembly, the massive inertia and boundary stiffness of the support structure will dominate the dynamic system. In practice, this dynamic coupling introduces significant interface damping, suppresses high-frequency response amplitudes (typically above 1.2 kHz), and blends the component's natural modes with the structural signature of the surrounding vessel. Consequently, in this constrained environment, advanced post-processing techniques become indispensable. Engineering teams must rely on quantitative modal correlation metrics, such as the Modal Assurance Criterion (MAC), to filter out fixture-dominated dynamics and accurately identify, pair, and isolate the mode shapes that genuinely belong to the component under investigation.



ITERATIVE FEA CALIBRATION VIA THE HALF-POWER BANDWIDTH METHOD

Once the free-free experimental response is captured, numerical model correlation can be performed. High-fidelity finite element models can achieve strong agreement with baseline experimental ping tests, typically capturing the lower, dominant global modes, such as torsional, pure flexural, and mixed flexural-torsional modes, within frequency deviations in the range of 5–10%, and under 7% for primary structural modes.

In an early prototyping phase, accepting a slightly broader tolerance on natural frequencies is essential. During initial development, the Additive Manufacturing processes themselves are still being refined for repeatability, and local geometric or microstructural variations inevitably introduce scatter in the dynamic response. As the design and manufacturing parameters mature, this tolerance window is progressively tightened. However, due to inherent process-induced variability in metal AM, frequency deviations rarely fall below a threshold of ±3%. Accounting for this realistic margin is critical during the subsequent dynamic assessment phase: engineering teams must factor this frequency uncertainty band directly into Campbell or Campbell-like Campbell-diagram evaluations to ensure safe operational margins against machine forcing frequencies and combustion instabilities. Meanwhile, higher-order local modes (typically above 2 kHz) exhibit significantly lower mass participation, making their experimental excitation and numerical matching less critical for overall structural integrity.

To refine the FEA model's structural damping beyond arbitrary loss factors, an iterative calibration based on the Half-Power Bandwidth Method (HBM) is applied. The viscous damping ratio ξ is extracted around specific mode peaks by measuring the bandwidth Δf at the −3 dB (70.7% amplitude) power points relative to the natural frequency f_n:

$$\xi = \frac{\Delta f}{2 f_n}$$

Starting from raw experimental damping measurements, which often yield extremely low values (on the order of 0.05%–0.1%) for low-mass, rigid AM components, these empirical inputs are fed back into the numerical model. The FEA structural damping parameters are then iteratively tuned until the simulated frequency response bandwidth (Δf) matches the experimental bandwidth across all target modes.

In an early prototyping phase, this iterative optimization transforms raw, incomplete experimental measurements into a robust, mode-calibrated numerical model. By replacing generic material assumptions with mode-specific damping parameters, design teams obtain a reliable baseline to evaluate operational dynamic stresses, refine structural geometries, and mitigate high-cycle fatigue (HCF) risks.

Furthermore, establishing a calibrated FEA model early in the development loop is highly cost-effective. It provides the necessary dynamic foundation before committing to more complex, time-consuming, and expensive experimental campaigns, such as full-scale shaker table testing or operational hot-gas testing, which are typically reserved for advanced validation stages as the component design and manufacturing process reach maturity.

PRACTICAL IMPLICATIONS FOR ASSET RELIABILITY

As the power generation sector accelerates its transition toward high-hydrogen fuels, mechanical assets face an increasingly demanding dynamic environment. AM offers unprecedented freedom to design high-performance, hydrogen-ready turbine components, but it requires a fundamental shift in how structural integrity and dynamic response are evaluated.



For engineering managers, maintenance leads, and asset reliability teams, managing this transition effectively relies on three core operational principles:

Treating damping as a primary design parameter:

Structural damping can no longer be an after-thought or a generic constant plugged into an FEA solver. Because microstructural anisotropy, porosity, and surface roughness directly alter energy dissipation, evaluating damping alongside aerodynamic and thermal performance from the initial prototyping phase is essential to prevent high-cycle fatigue (HCF);

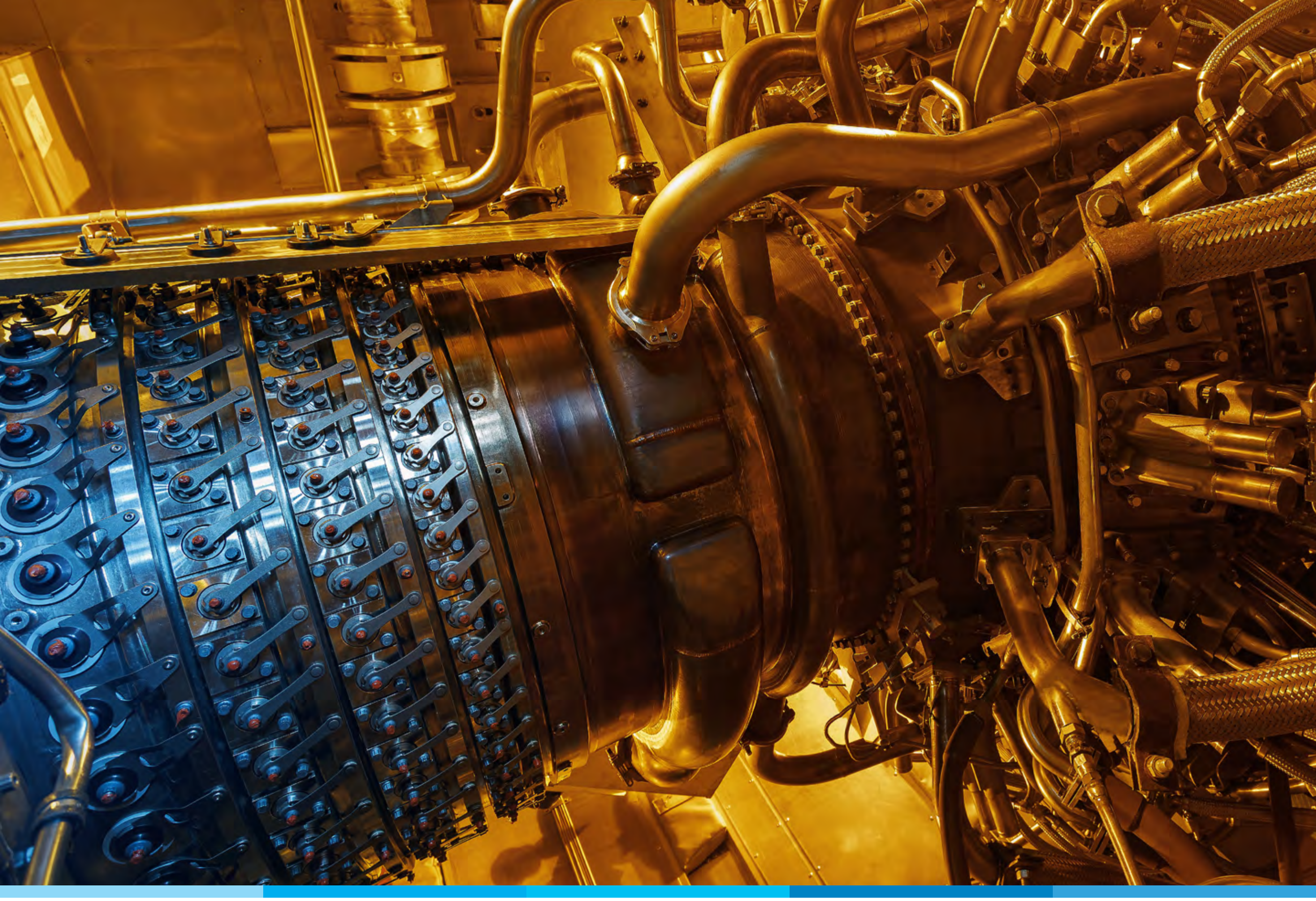
Adopting a progressive calibration strategy:

Relying solely on uncalibrated numerical models creates severe operational risks. Establishing a clear, step-by-step framework, starting with free-free ping testing, refining loss factors via the half-power bandwidth method (HBM), and accounting for realistic process-induced frequency margins (±3%), allows engineering teams to de-risk component designs before committing to expensive, full-scale testing on shaker tables or hot-gas rigs;

Ensuring joint integrity and boundary condition stability:

A calibrated numerical model is only as reliable as the boundary conditions of the real assembly. Securing mechanical interfaces and bolted connections against vibration-induced loosening is paramount. Preventing micro-slip degradation and maintaining stable preloads ensures that actual operational dynamics match predicted behaviors, protecting critical assets against unexpected degradation and costly unplanned outages.

By combining advanced manufacturing with rigorous, mode-calibrated dynamic testing and uncompromising joint stability, power generation teams can fully unlock the efficiency of hydrogen combustion while guaranteeing the high availability and long-term reliability required by modern energy infrastructure.



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