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A Review of Multi-Axial Fatigue Testing Machines in Structural Engineering

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ABSTRACT :

Structural components such as offshore jacket platform members, tubular joints, wind turbine towers, bridge connections, and pressure-retaining piping are rarely subjected to purely uniaxial cyclic loading in service; they experience combined axial, bending, torsional, and internal-pressure loading arising from wave action, wind, seismic excitation, and operational loads. Multi-axial fatigue testing machines have therefore become essential tools for characterizing material and connection behavior under realistic, combined loading histories. This paper reviews the design principles, classification, instrumentation, and control strategies of multi-axial fatigue testing machines, and compares representative testing rigs reported in the literature in terms of loading capacity, control methodology, and specimen geometry. Applications of these machines in structural engineering, particularly offshore and marine structures, are discussed, along with the principal challenges associated with non-proportional loading control, specimen design, and standardization. The review concludes by identifying emerging trends, including AI-assisted fatigue-life prediction and combined multi-axial corrosion-fatigue testing, which are expected to shape the next generation of multi-axial fatigue test systems.

Keywords: Multi-axial fatigue; fatigue testing machine; non-proportional loading; tubular joints; offshore structures; biaxial testing; axial-torsion.

1. Introduction

Fatigue remains one of the most common causes of structural failure in engineering systems subjected to repeated or fluctuating loads. While uniaxial fatigue testing has historically formed the basis of material characterization and design codes, real structural components are almost never loaded along a single axis. Offshore jacket platforms subjected to combined wave, current, and seismic loading; wind turbine support structures under wind and rotor-induced loading; and bridge deck-to-girder connections under traffic and thermal loading all experience simultaneous, often out-of-phase, combinations of axial force, bending moment, torsion, and, in some cases, internal or hydrostatic pressure. Designing against fatigue failure under such conditions requires experimental data generated under genuinely multi-axial and, where relevant, non-proportional loading paths.

Multi-axial fatigue testing machines are purpose-built systems capable of applying two or more independently controlled load or displacement channels to a specimen, with the ability to vary the relative phase, amplitude, and frequency between channels. This capability distinguishes them from conventional single-actuator uniaxial fatigue rigs and allows the reproduction of proportional loading (where principal stress directions remain fixed) as well as non-proportional loading (where principal stress directions rotate during the loading cycle), the latter being known to cause additional cyclic hardening and accelerated fatigue damage in many metals.

This review synthesizes the state of the art in multi-axial fatigue testing machine design, classifies existing systems, compares their capabilities, and highlights their role in structural engineering applications, with particular emphasis on offshore and marine structures where combined environmental loading makes multi-axial fatigue assessment indispensable.

2. Classification of Multi-Axial Fatigue Testing Machines

Multi-axial fatigue testing machines can be broadly classified according to the combination of loading modes they apply:

2.1 Axial-Torsion Servo-Hydraulic Systems

These are the most widely used multi-axial testing machines, combining a linear actuator for axial load/displacement with a rotary actuator for torque/twist on a single load frame. They are typically used with tubular or solid round-bar specimens and allow independent control of axial and torsional load or strain, including control of the phase angle between the two channels to simulate proportional or non-proportional loading.

2.2 Biaxial and Triaxial Cruciform Machines

Cruciform specimen rigs use two, three, or four independently controlled actuators arranged orthogonally in a plane to apply in-plane biaxial tension-tension or tension-compression loading to a cross-shaped (cruciform) specimen. These systems are particularly relevant for thin-walled structural plates and shell elements, where multi-axial in-plane stress states dominate.

2.3 Combined Tension-Torsion-Internal Pressure Rigs

For tubular structural members such as offshore risers, pipelines, and pressure vessels, testing rigs combine axial load, torque, and internal (or external) hydrostatic pressure. These systems reproduce the combined hoop, axial, and shear stress states experienced by pressurized tubular components under service loading.

2.4 Bending-Torsion Machines

Bending-torsion rigs, including rotating-bending-with-superimposed-torsion configurations, are widely used for shafts and notched components in mechanical and automotive structural applications, and remain relevant to structural connections subjected to combined flexural and torsional cyclic loads.

2.5 High-Frequency Piezoelectric / Ultrasonic Multi-Axial Systems

For very-high-cycle fatigue (VHCF) regimes beyond 10^7 - 10^9 cycles, ultrasonic resonance-based systems operating near 20 kHz have been adapted to superimpose torsional loading on axial excitation, drastically reducing test duration compared with conventional servo-hydraulic systems.

3. Machine Design and Loading Mechanisms

The core design decisions in a multi-axial fatigue testing machine concern the actuation method, load-frame configuration, specimen geometry, and control strategy. Servo-hydraulic actuation remains dominant for high-capacity, low-to-medium frequency multi-axial testing due to its high force density and dynamic range, while servo-electric actuation is increasingly used for lower-capacity, higher-precision applications. Load frame configurations vary between single-actuator systems with mechanical load-splitting to derive a secondary loading mode, and fully independent multi-actuator systems that allow arbitrary control of amplitude and phase between channels but require sophisticated real-time control to manage crosstalk between axes.

Specimen geometry is closely linked to machine configuration: tubular specimens are standard for axial-torsion and combined pressure rigs, cruciform specimens are used for in-plane biaxial systems, and notched round-bar or dogbone specimens are used for bending-torsion configurations. Control strategy — load control, strain control, or mixed-mode control — is selected based on whether the test targets high-cycle (load-controlled) or low-cycle (strain-controlled) fatigue regimes. Phase-angle control between loading channels is essential for non-proportional loading studies and represents one of the more demanding real-time control challenges in multi-axial testing machine design.

4. Instrumentation and Data Acquisition

Accurate multi-axial fatigue testing depends on instrumentation capable of resolving combined strain states. Biaxial strain gauge rosettes and biaxial extensometers remain the standard for point-wise strain measurement, while digital image correlation (DIC) has become increasingly common for full-field strain mapping, particularly on cruciform and plate specimens where strain concentrations may develop away from the specimen Centre. Load cells and torque transducers must be configured to decouple the individual loading channels and closed-loop control systems must actively compensate for crosstalk between axial, torsional, and pressure channels to maintain the intended loading path, especially under non-proportional conditions.

5. Comparative Review of Existing Testing Rigs

Table 1 summarizes representative multi-axial fatigue testing machines and rigs reported in the literature, compared in terms of loading mode, capacity, control methodology, specimen type, and typical structural engineering application.

Table 1: Comparative summary of representative multi-axial fatigue testing machines

Machine / Rig Type	Loading Mode	Capacity	Control Type	Typical Specimen	Reported Application
MTS Bionix Axial-Torsion	Axial + Torsion (in/out of phase)	± 100 kN / ± 1000 N·m	Servo-hydraulic, load/strain control	Tubular / cylindrical	Tubular joint fatigue, welded connections

Machine / Rig Type	Loading Mode	Capacity	Control Type	Typical Specimen	Reported Application
Cruciform Biaxial Rig	In-plane biaxial tension	± 50 -250 kN per axis	Independent 2/4-actuator servo-hydraulic	Cruciform (cross-shaped)	Plate fatigue, thin-walled structural panels
Instron 8874/8862 Combined Axial-Torsion	Axial + Torsion	± 25 kN / ± 100 N·m	Servo-electric/hydraulic, closed-loop	Round-bar / hollow tube	Material characterization, notch fatigue
Tension-Torsion-Internal Pressure Rig	Axial + Torsion + Internal pressure	Pressure up to 70 MPa	Multi-channel servo-hydraulic	Thick-walled tubular	Offshore riser & pipeline fatigue
Bending-Torsion Fatigue Machine	Rotating/plane bending + Torsion	Variable, typ. ± 500 N·m	Mechanical/servo-hydraulic hybrid	Shaft / notched bar	Automotive and machinery shafts
Ultrasonic Multiaxial VHCF Rig	Axial + superimposed torsion, high frequency	~ 20 kHz resonance	Piezoelectric actuation	Hourglass specimen	Very high cycle fatigue ($>10^8$ cycles)

6. Applications in Structural Engineering

6.1 Offshore and Marine Structures

Offshore jacket platform members and their tubular joints are subjected to combined axial, bending, and torsional stresses arising from wave, current, and earthquake loading, often superimposed on internal or external hydrostatic pressure. Multi-axial fatigue testing of tubular joint specimens under combined loading, guided by design codes such as DNVGL-RP-C203, provides the S-N and stress concentration factor data used in fatigue design of jacket structures, directly supporting the kind of nonlinear seismic and wave-loading assessment used in offshore jacket platform research.

6.2 Wind Turbine Support Structures

Monopile and jacket-type wind turbine foundations experience millions of load cycles from combined wind and wave action, requiring multi-axial fatigue data at both high-cycle and very-high-cycle regimes.

6.3 Bridge Components and Pressure Systems

Bridge bearings, orthotropic deck welds, and pressurized piping systems similarly experience combined loading, and multi-axial fatigue testing supports fatigue-resistant detailing and remaining-life assessment for these components.

7. Challenges and Limitations

Despite significant advances, several challenges persist in multi-axial fatigue testing machine design and use. Achieving true non-proportional loading at higher frequencies is constrained by actuator bandwidth and control-loop latency. Cruciform specimens are prone to premature failure at fillet or gauge-section edges rather than the intended central region, complicating interpretation of results. Multi-actuator systems entail substantial capital cost and control complexity relative to uniaxial systems. Furthermore, standardization remains incomplete: unlike uniaxial fatigue testing, which is well covered by standards such as ASTM E466, no single standard comprehensively addresses multi-axial fatigue testing procedures across all loading combinations, leading to variability in reported test methodologies across the literature.

8. Recent Advances and Future Directions

Emerging directions in multi-axial fatigue testing include the integration of machine-learning-assisted fatigue-life prediction models trained on multi-axial test databases, development of more compact and cost-effective multi-actuator rigs, and combined multi-axial corrosion-fatigue testing systems

capable of applying simultaneous mechanical loading and corrosive or marine environmental exposure a capability of particular relevance to offshore structures operating in marine environments with soil-pile-structure interaction effects.

9. Conclusion

Multi-axial fatigue testing machines play a critical role in generating the experimental data needed to assess fatigue performance of structural components under realistic, combined loading conditions. This review has classified the principal machine configurations, summarized their design and control characteristics, compared representative systems reported in the literature, and discussed their application in structural engineering, particularly offshore structures. Continued development of higher-bandwidth control systems, standardized testing procedures, and combined environmental-mechanical testing capability will be essential to meet the growing demand for multi-axial fatigue data in the design of offshore, wind, and marine infrastructure.

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