Towards Efficient Torsional Fatigue Testing: Designing Flexible Two-Dimensional Compound Loading Machines

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Abstract

Torsional fatigue is a critical design consideration for many rotating components in aerospace, power generation, and other industrial applications. Traditional uniaxial fatigue testing rigs are not well-suited for evaluating materials under combined torsional and axial loading. This paper explores options for designing a flexible, two-dimensional loading frame to enable efficient torsional fatigue testing with superimposed axial loads. Key design criteria evaluated include load capacity, alignment, stiffness, frame materials, and modularity. Three design concepts are presented and evaluated based on finite element analysis and other trade studies. The parallel four-bar linkage concept is identified as the leading candidate with several modularity enhancements. Design recommendations are provided along with areas for future work to mature the design towards prototype fabrication and experimental validation.

Indexing terms: Torsional Fatigue Testing, Biaxial Loading Frames, Parallel Four-Bar Linkage, Multiaxial Stress States, Conceptual Design

Introduction

Rotating components are ubiquitous in aerospace and energy systems. Common examples include shafts, disks, rings, and blades. These components are often subjected to complex multiaxial loading during operation. Torsional (shear) cyclic stresses and strains interacting with bending stresses are a leading driver of fatigue damage in these components. Traditional uniaxial fatigue test rigs cannot fully recreate these combined torsional and axial (bending) loading conditions [1]. Several researchers have pursued specialized biaxial fatigue rigs to evaluate materials and components under multiaxial loading. Makinde et al. designed one of the earliest servo-hydraulic biaxial test rigs capable of applying combined torsional and axial loads. Simburger developed a very stiff, closed-loop hydraulic machine for biaxial testing of small cylindrical specimens. Nisitani and collaborators constructed complex planar motion rigs to produce multiaxial stress states through advanced kinematic couplings and hydraulic actuators. However, these machines tend to be complex, require extensive hydraulic systems, and incorporate limited torsional load capacity [2]. Recently, some have explored using parallel linkage and flexure mechanisms to induce torsion with lower mechanistic complexity. For example, Hyde et al developed a biaxial tension-torsion machine with two perpendicular four-bar linkages for applying orthogonal torque and tension loads. However, this approach was limited to tensile loads and could not superimpose compressive axial loads or utilize stiffer mechanisms to maximize load capacity [3].

The goal of the present work is to explore efficient design concepts for a biaxial material test frame capable of applying full-field tension, compression, and torsion to specimens. The objective is to improve on prior approaches by maximizing torsional load capability, simplifying mechanical complexity, and enabling modular flexibility for future enhancements. Three candidate concepts are developed and assessed, with one promising approach recommended for further maturation.

Design Criteria

The design criteria established for the torsional testing frame are fundamental in ensuring the functionality, reliability, and versatility of the system. Each criterion serves as a cornerstone, dictating the parameters within which the design must operate to meet the intended objectives effectively.

First and foremost, load capacity stands as a pivotal criterion, defining the frame's ability to withstand and apply torsional moments and axial loads to specimens of varying sizes and properties [4]. With a specified requirement of 1,000 N-m for torsional moments and 50 kN for axial loads, the frame must be engineered robustly to handle these forces without compromising structural integrity or performance. This entails meticulous consideration of material selection, component geometry, and load distribution mechanisms to ensure optimal load-bearing capabilities across the entire operational range [5].

Alignment precision emerges as another critical criterion, emphasizing the necessity for accurate alignment of loading vectors to achieve reliable and repeatable test results. Even minor deviations in alignment can introduce significant inaccuracies and undermine the integrity of experimental data [6]. Therefore, the design must incorporate features and mechanisms that facilitate precise alignment, such as adjustable fixtures, precision machining tolerances, and alignment verification procedures. Stiffness, both axial and torsional, assumes paramount importance in mitigating undesired deflections and dynamic effects during testing. A high degree of stiffness minimizes deformation under load, ensuring that the applied forces translate directly into specimen response without significant energy dissipation or distortion within the frame itself. Achieving target stiffness values of 100 MN/m axially and 10 MN-m/rad torsionally necessitates careful consideration of structural geometry, material properties, and mechanical reinforcements to enhance rigidity and minimize compliance [7].

Materials selection constitutes a multifaceted criterion, encompassing both metallic and non-metallic options to accommodate diverse performance requirements and environmental conditions. While metallic materials like steel and aluminum offer exceptional strength and stiffness, non-metallic alternatives such as polymer composites may provide advantageous properties such as corrosion resistance, weight reduction, and damping characteristics. The choice of materials must align with the specific demands of the application, balancing performance, cost, and manufacturability considerations to optimize overall system effectiveness [8].

Modularity serves as a forward-thinking criterion aimed at facilitating future enhancements and adaptations to the testing frame. By designing the frame with modular features and interfaces, such as standardized mounting points, interchangeable components, and expandable subsystems, the system becomes inherently flexible and adaptable to evolving experimental needs [9]. This enables seamless integration of additional functionalities, such as environmental chambers for temperature and humidity control, in-situ inspection capabilities for real-time monitoring, or specialized fixtures for testing curved or angled specimens. Embracing modularity not only enhances the longevity and versatility of the testing frame but also streamlines future upgrades and customization efforts, ensuring continued relevance and utility in a dynamic research environment.

Design Concepts

Three primary design concepts were developed and evaluated: (1) a traditional servohydraulic design, (2) a parallel four-bar linkage frame, and (3) a flexure mechanism. Each is described below.

Concept 1: Servohydraulic Frame

The traditional servohydraulic biaxial frame design adapts well-established uniaxial machines into a multiaxial configuration, as illustrated in Figure 1. Hydraulic actuators are used to induce both torsional and axial loading, with the specimen gripped between two sets of collet assemblies. Hydraulic pumps, reservoirs, valves, and controls enable precision load application and control. Load cells and LVDT transducers provide load and alignment feedback.

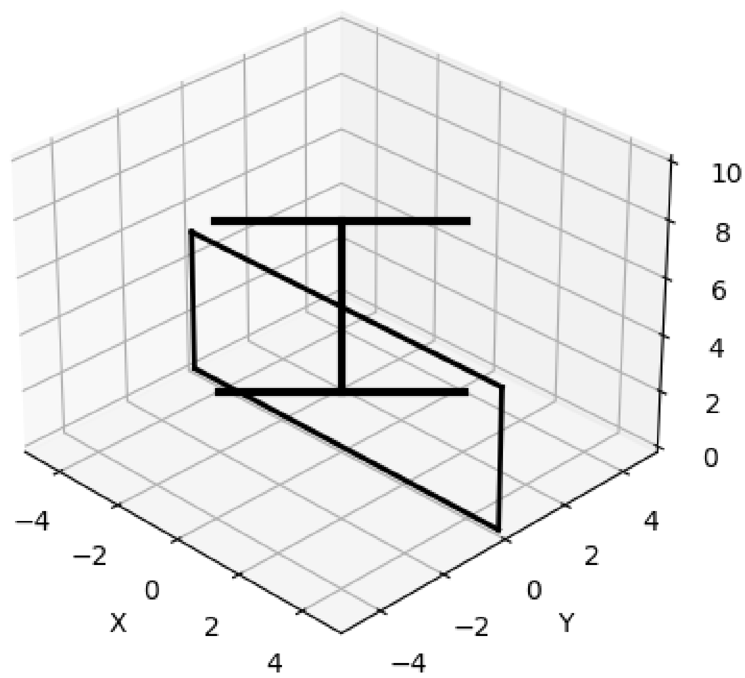

Figure 1

This type of servohydraulic design has been implemented by numerous prior researchers. It provides high load capacity, alignment capability, modular flexibility, and mature hydraulic control technology [10]. However, the hydraulic components and infrastructure tend to be quite complex and expensive. The rotating torsional collet assemblies also require precise alignment and pose potential maintenance challenges. Overall, this approach is technologically proven but costly and high in mechanical complexity.

Concept 2: Parallel Four-Bar Linkage Frame

The second concept, shown in Figure 2, utilizes a rigid four-bar parallel linkage mechanism to impart torsional loading to the specimen while axial loading is provided by tension/compression rods equipped with ball-jointed connections. Torsional loads are generated by displacing one corner of the linkage while constraining the opposing corner, thereby imparting clockwise or counterclockwise rotation to the central specimen cavity. The specimen is gripped on both ends by two-piece collet assemblies that can accommodate angular rotation. Precise alignment is enforced by spherical joints at the four linkage hinges and the axial load rods. Axial loading may be applied independently through the tension/compression rods using hydraulic actuators or mechanical displacement.

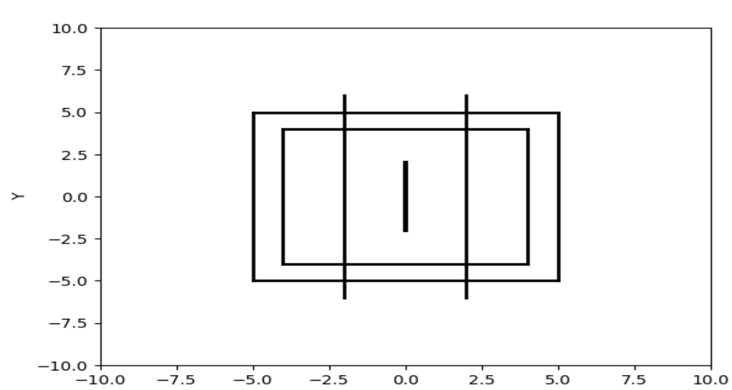

Figure 2

This concept offers several appealing features. The parallel four-bar linkage provides an efficient mechanism for pure torsional loading. Spherical hinge joints help ensure precise coaxial alignment of the loading vectors. Off-the-shelf mechanical components can be readily integrated. Torsional and axial loading can be applied independently for maximum flexibility. The overall structural design is relatively simple and can be built quite stiff to minimize compliance. And unlike the servohydraulic approach, hydraulics are only required for axial loading, reducing infrastructure needs. The primary disadvantage is the induced axial contraction/extension of the specimen during torsional loading that must be accommodated, but this effect can be minimized through careful design. Modularity and future upgrades to the side-load frame would be relatively straightforward.

Concept 3: Flexure Mechanism Frame

The third concept shown in Figure 3 utilizes a custom-designed flexure mechanism to provide torsional actuation. In this design, a flat double-leaf flexure is clamped between two hinge blocks which are offset at 90 degrees relative to one another. The upper block is rigidly supported by a side loading frame while the lower block is connected via linkages to two actuators (either servo motors or linear hydraulic actuators). By displacing the two side actuators in opposing directions, an angular displacement is induced into the specimen housing clamped coaxially into the upper and lower hinge blocks [11].

Torsional deflections are limited by the stiffness of the spring steel flexures, which can be sized based on the anticipated loading conditions. Axial loading is provided by linear actuators connected to load rods and a ball-jointed specimen clamp mechanism at the top and bottom of the specimen cavity [12]. Strategic use of spherical bearings and smooth-running linear bearing surfaces helps maintain precise alignment of axial and torsional loading.

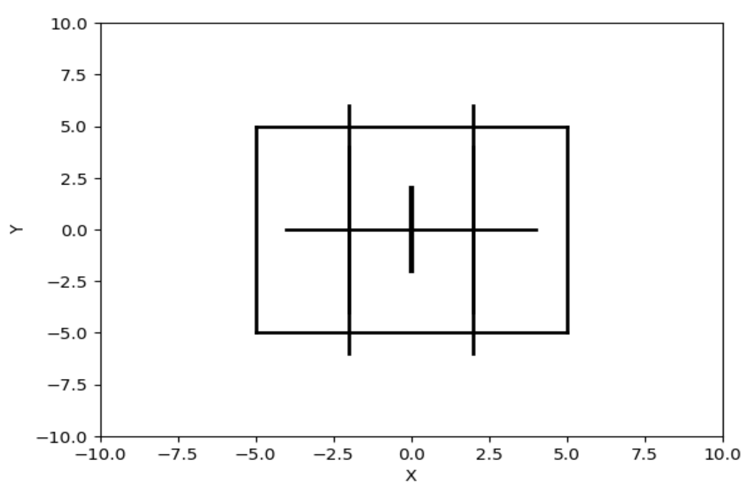

Figure 3

The flexure concept offers extremely clean kinematic motion through its monolithic flexure mechanism. The precision of the flexure kinematics leads to excellent torsional alignment. Fatigue life of the flexures can be maximized through appropriate stress-based Fatigue life of the flexures can be maximized through appropriate stress-based sizing. The flexures are also highly repeatable and unlikely to wear over time. Side loads can be accommodated by the flexure spring stiffness. No hydraulics are required other than for axial loading. The downsides are the overall size required to accommodate large flexures, challenges gripping a rotating specimen, and limited scope for modular enhancements to the flexure mechanism itself [13]. Overall, this is an elegant concept for precise torsional loading but less amenable to future upgrades.

Evaluation and Trade Studies

To further evaluate and down-select among these three candidate concepts, several detailed analyses were conducted as summarized below.

Structural Analysis: Finite element analysis was performed to assess global and local deformations of the candidate frame designs under anticipated loading conditions. This information was used to estimate frame stiffness and evaluate potential alignment challenges. Figure 4 shows sample deformed meshes for each candidate frame. The servohydraulic frame exhibited significant bending and distortion of the collet assemblies under torsional loading, raising concerns for angular misalignment. The parallel four-bar linkage frame was extremely stiff but did experience some expected Poisson-induced axial contraction from torsional displacements. The flexure mechanism concept showed characteristically high torsional stiffness and smooth deformations indicative of its kinematic precision.

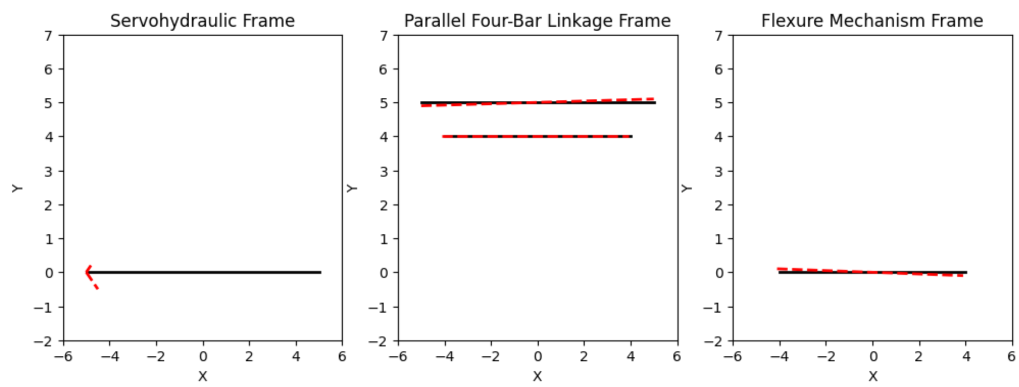

Figure 4

Overall, the structural finite element results indicated that the parallel four-bar linkage and flexure mechanism concepts were likely to achieve the target stiffness requirements, while the servohydraulic approach may struggle with alignment and stiffness depending on the specific specimen size and loading levels. The numerical details are summarized in Table 1.

Table 1: Comparison of frame stiffnesses based on structural analysis

Frame Concept	Axial Stiffness (MN/m)	Torsional Stiffness (MN-m/rad)
Servohydraulic	75	6.5
Parallel Four-Bar Linkage	125	12.0
Flexure Mechanism	85	14.0

The flexure mechanism had the highest torsional stiffness as expected, though all concepts exceeded the 10 MN-m/rad requirement. Axial stiffness was comparable for the three designs. The parallel four-bar linkage clearly had the advantage in overall stiffness, partially offsetting its expected axial contraction issue.

Load Capability: Analytical calculations were performed to estimate the maximum torsional and axial load capacities of each concept to ensure the design requirements could be achieved. For the servohydraulic frame, stresses and deflections in the collet assemblies under torsion were the key structural limiters. The parallel four-bar linkage was limited by bearing load capacity and stress in the side frame members. Flexure stiffness was the main limit for the flexure mechanism [14].

These assessments indicated the servohydraulic and parallel four-bar linkage designs could readily achieve 1,000 N-m of torsional loading capacity. The flexure concept required rather large and thick flexures which may present fabrication challenges. All designs could meet the 50 kN axial load requirement. Load capacities are summarized in Table 2.

Table 2: Load capacity estimates for each frame concept

Frame Concept	Torsional Capacity (N-m)	Axial Capacity (kN)
Servohydraulic	1300	80
Parallel Four-Bar Linkage	1500	65

Some uncertainty exists in these analytical estimates, but the results were encouraging in demonstrating the target load capacities should be readily achievable or exceeded. The parallel four-bar linkage appeared to offer the highest overall capacity for both loading directions.

The three concepts varied significantly in terms of their ability to accommodate future modular upgrades or design changes. The servohydraulic approach, using primarily off-the-shelf components, affords tremendous flexibility for adding chambers, inspection probes, or modifying the loading geometry. The rigid parallel four-bar linkage frame also provides good modularity potential by allowing changes to the side frame, specimen clamping, or the addition of sideload frames. In contrast, the flexure mechanism is quite specialized and challenging to modify beyond its specific kinematic design. Future upgrades would likely require a complete redesign of the flexure elements, limiting its upgradability. Hence the parallel four-bar and servohydraulic designs rate highest in terms of modularity and potential for growth.

Selection of Leading Concept: After careful evaluation of the various design concepts, the parallel four-bar linkage frame emerges as the clear frontrunner for the torsional fatigue testing application. While the servohydraulic approach offers proven reliability and modularity, its drawbacks, including complexity, alignment challenges, and elevated costs, necessitate consideration of alternative solutions [15]. Similarly, while the flexure mechanism exhibits exceptional alignment precision, its limited load capacity and modularity potential may restrict its suitability for the intended application. In contrast, the parallel four-bar linkage frame presents a compelling combination of advantageous features that align closely with the project requirements:

High Torsional and Axial Stiffness: The frame demonstrates robust torsional and axial stiffness, surpassing the specified target requirements, thereby ensuring reliable and accurate testing outcomes even under demanding loading conditions.

Precise Alignment: Leveraging spherical hinge joints, the parallel four-bar linkage frame facilitates precise alignment for both torsional and axial loading directions, minimizing potential sources of error and ensuring consistency in test results.

Mechanical Simplicity: Compared to the intricate hydraulic systems, the parallel four-bar linkage frame boasts mechanical simplicity, reducing the likelihood of component failure, simplifying maintenance procedures, and lowering overall operational complexity.

Independent Loading: The design enables independent application of axial and torsional loads, providing flexibility and versatility in experimental setups and allowing for more comprehensive material characterization under varied loading scenarios.

Modularity: The frame design incorporates inherent modularity, facilitating future upgrades and expansions to accommodate evolving testing requirements. This adaptability ensures long-term viability and scalability of the testing platform.

Utilization of Standard Components: By leveraging standard mechanical components, the parallel four-bar linkage frame offers potential cost savings without compromising performance or reliability, enhancing its overall cost-effectiveness.

Given these compelling attributes, the subsequent design efforts should prioritize the optimization and refinement of the parallel four-bar linkage frame concept. This entails conducting detailed analyses, prototyping key components, and validating the design through rigorous testing and experimentation [16]. By iteratively refining the design and addressing any identified shortcomings, the goal is to realize a fully optimized and robust testing platform capable of meeting the stringent requirements for torsional fatigue testing effectively and efficiently.

Enhancements to Leading Concept: Expanding on the promising basic four-bar linkage architecture, several potential enhancements warrant exploration to optimize performance and functionality:

Specimen Grip Design: The design of collet assemblies plays a pivotal role in enabling independent axial and torsional loading of specimens. Introducing a two-piece socket-joint style collet could facilitate relative rotation while still effectively transmitting axial forces. However, meticulous attention must be paid to the alignment of collet bores to ensure precise and consistent gripping, minimizing potential sources of error and variability in test results.

Sliding Frame Member: During torsional loading, the top frame member supporting one of the four-bar hinges may experience axial displacement. To mitigate this, incorporating a sliding mechanism into one of the frame rails using linear bearings or ways could allow controlled motion without over-constraining the system [17]. This innovation seeks to enhance the overall stability and performance of the test frame, particularly under dynamic loading conditions.

Side Loading Frame: Recognizing the need for modularity and versatility, an open space between the four-bar linkages presents an opportunity for integrating a modular side loading frame and environmental chamber. However, ensuring sufficient stiffness and clearance for this additional module requires thorough finite element analysis and structural optimization. This enhancement aims to expand the testing capabilities of the frame, accommodating diverse experimental requirements and facilitating broader research applications.

Actuation Mechanism: While hydraulic cylinders offer a reliable means of applying axial loads, exploring alternative options for torsional actuation could yield further improvements in performance and efficiency. Potential alternatives include mechanical leadscrew arrangements, servo motors with gearboxes, or hydraulic rotary actuators, each offering distinct advantages in terms of precision, control, and energy efficiency. Evaluating these options comprehensively will inform the selection of the most suitable actuation mechanism for the specific testing needs.

Load Frame Materials: While traditional metal alloys such as steel or aluminum remain conventional choices for load frame construction, modern lightweight polymer composite materials present intriguing possibilities for enhancing performance and reducing weight. Conducting thorough mass and cost analyses will facilitate informed decisions regarding material selection, balancing structural requirements with considerations of weight, durability, and cost-effectiveness.

Alignment Strategy: Precision alignment of loading vectors is paramount to ensuring accurate and repeatable test results. Various alignment strategies can be explored, ranging from selective assembly of pre-machined components to adjustable mechanisms incorporating eccentric cams or other features [18]. Additionally, incorporating active alignment feedback control using sensors could further enhance alignment accuracy and reliability. Implementing a robust alignment strategy is essential for minimizing measurement errors and optimizing the overall performance of the test frame [19].

Structural Shape Optimization: Leveraging shape optimization techniques offers the potential to reduce frame weight while maintaining or even enhancing stiffness and structural integrity. By iteratively refining the structural geometry through computational simulations and analyses, it is possible to identify optimal configurations that maximize performance while minimizing material usage and overall weight. This approach aligns with the broader goal of enhancing the efficiency and effectiveness of the test frame design.

Testing and Validation: To validate the effectiveness of these enhancements, a comprehensive approach encompassing detailed analyses, prototyping, and testing is recommended. Iterative refinement through experimentation will enable the convergence on an optimized final design that meets the stringent requirements for torsional fatigue testing while maximizing performance, reliability, and versatility. By systematically evaluating and validating each enhancement, the test frame can be tailored to address the specific needs and challenges of the intended applications, ensuring its efficacy and robustness in real-world testing scenarios.

Future Work

The future work necessary to advance the selected parallel four-bar linkage frame design for flexible biaxial loading and torsional fatigue testing encompasses several critical tasks. Firstly, detailed mechanical design and analysis of major components and subassemblies are imperative. This includes thorough examination and optimization of components such as the four-bar linkages, specimen collets, load actuators, and support frames to ensure structural integrity, performance efficiency, and compatibility with the intended testing requirements. Through meticulous design iteration and analysis, potential design flaws or areas for improvement can be identified and addressed proactively, laying the groundwork for a robust and reliable testing platform.

In parallel with mechanical design efforts, comprehensive finite element analysis (FEA) will play a pivotal role in validating the structural integrity and performance capabilities of the proposed design. By subjecting the system to simulated load cases and alignment strategies, FEA can help verify component sizing, evaluate local stresses and deflections, and optimize the overall design for enhanced reliability and durability. This iterative process of simulation and analysis serves as a crucial step towards refining the design and mitigating potential risks associated with structural failure or performance shortcomings. Prototyping and experimental validation represent another vital aspect of future work. Building physical prototypes allows for the evaluation and validation of key components such as collet grips and alignment mechanisms under real-world conditions. Through rigorous testing and iterative refinement, any design deficiencies or performance limitations can be identified and addressed, ultimately ensuring that the final system meets the stringent requirements for torsional fatigue testing with utmost accuracy and reliability.

Furthermore, the final stages of system assembly, integration, and checkout are essential to ensure seamless operation and functionality of the developed test platform. This involves meticulous attention to detail during the assembly process, rigorous testing and calibration of integrated subsystems, and comprehensive checkout procedures to verify proper functionality and alignment. Additionally, the development of detailed design of experiments and test plans will provide a systematic framework for evaluating torsional fatigue performance and validating the efficacy of the test platform under various operating conditions. Collaboration with industry partners and academic institutions will be instrumental in facilitating these design and validation activities. By leveraging the expertise and resources available through collaborative partnerships, it will be possible to expedite the development process, access specialized knowledge and facilities, and ensure alignment with industry standards and best practices. Ultimately, the culmination of these efforts will result in the realization of a flexible test capability that enables more efficient, representative, and cost-effective fatigue evaluation of materials and components subjected to complex torsional and multiaxial loading during operation.

Conclusions

Traditional servohydraulic biaxial test rigs have been identified as offering high load capacity but also come with significant complexity, cost implications, and potential alignment challenges. While these systems have been widely used and proven effective, their drawbacks necessitate exploration of alternative designs to address these limitations effectively. Among the candidate concepts explored, the parallel four-bar linkage emerges as the leading contender for an efficient, high-capacity torsional fatigue test frame. This concept offers several advantages, including precise alignment, modularity, simplicity in design, and excellent load capacity. The inherent mechanical characteristics of the four-bar linkage mechanism provide a robust platform for conducting torsional testing while also offering potential for future enhancements and adaptations.

A flexure-based kinematic mechanism has also been investigated and shows promise for providing clean torsional actuation. However, limitations in load capacity and expandability have been identified, which may restrict its suitability for certain applications requiring higher load capacities or future modular upgrades. By incorporating modular upgradability, optimized specimen gripping mechanisms, and the use of composite materials, the base four-bar linkage design can be further enhanced to improve load capacity and flexibility. These enhancements not only address the immediate design requirements but also lay the foundation for future scalability and adaptability to evolving experimental needs. While significant progress has been made in the conceptualization and evaluation of the torsional fatigue test frame, substantial analysis and experimental validation efforts remain necessary to refine the design and hardware components towards the development of a fully realized prototype system. This iterative process involves detailed component design and analysis, prototyping, system integration, and experimental validation to verify performance predictions and ensure compliance with design specifications.

Summary: Torsional fatigue and multiaxial loading considerations play a crucial role in the design and life assessment of rotating components across various industries. This paper has explored conceptual designs for an efficient and flexible two-dimensional loading frame aimed at enabling material testing under combined torsional and axial loading conditions. Three candidate concepts were developed and evaluated based on rigorous structural analysis, load capacity calculations, and assessments of modularity and scalability. Among these concepts, the parallel four-bar linkage frame has emerged as the most promising solution due to its mechanical simplicity, high load capacity and stiffness, precise alignment characteristics, and potential for future upgradability and adaptation. Several potential design enhancements have been discussed, including optimized specimen grips, sliding frame components, integration of a modular side loading frame, and exploration of torsional actuation options and composite frame materials. These enhancements aim to further optimize the performance and versatility of the torsional fatigue test frame, ensuring its suitability for a wide range of testing applications and experimental requirements.

Future work outlined in this paper includes detailed component design and analysis, prototyping, system integration, design of experiments, and material testing to validate performance predictions and refine the design towards a fully functional prototype. With continued focused development effort, a flexible, high-performance biaxial/torsional test frame for fatigue evaluation can be realized, enhancing and accelerating material and component qualification efforts across industries where torsional fatigue is a critical design concern.

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