# FATIGUE & FRACTURE TESTING

*A system driven by a moving-magnet linear motor provides developers with an alternative to other technologies for many tension or bend-to-failure, fracture toughness, high-cycle fatigue, or crack-growth testing applications.*

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The wide variety of engineered materials currently being considered for cyclic load-bearing applications will require a substantial amount of new test data. Specifically, fatigue and fracture testing are needed for a broader array of materials over a wider range of conditions than ever before. Such tests enable prediction of whether engineered materials such as nanocomposites can replace traditional metals for dynamic load-bearing applications. In addition, smaller test specimens such as foils, fibers, and films, and even small devices such as micro-electromechanical devices, create unique testing requirements.

To test such materials and components, a new approach has been developed in which high-performance linear moving-magnet motors replace traditional servo-hydraulic, electro-mechanical, or voice coil technologies in fatigue and fracture test equipment. This article explains the benefits and describes typical test configurations with example data for a number of materials.

### Moving-magnet motor

A very different type of linear actuator known as a moving-magnet motor eliminates several of the drawbacks of traditional material testing technologies. Fig. 1 shows the typical configuration of the linear motor in a single-axis material test system. The magnetic portion of the moving-magnet motor is comprised of three basic elements: the magnet, the coils, and the core. The neodymium-iron-boron (NdFeB) magnet moves, while the coils and core remain stationary.

The core and coil combination may be viewed as an electromagnet producing a north and a south pole as a function of current. When the current is applied, the appropriate poles of the magnet are either attracted or repelled, producing the force. The stronger the current, the stronger the resulting force. The linear motor design offers the following benefits:

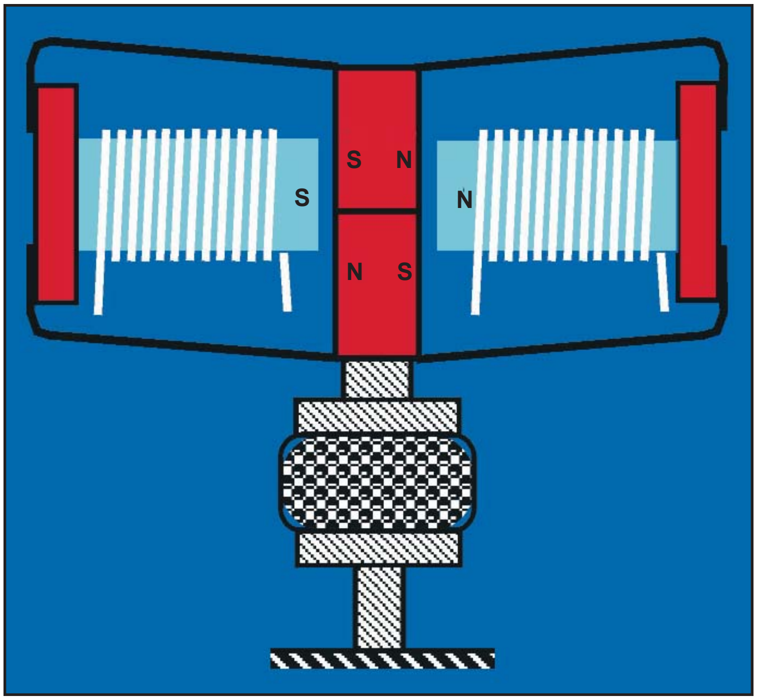

*Fig. 1 — Typical electromagnetic behavior of the moving-magnet motor. The Bose motor designs have been integrated into the EnduraTEC ELectroForce (ELF) Series of test instruments to evaluate fatigue and fracture properties.*

- *Forces and displacements:* The forces range from nanonewtons up to 6000 N, and displacements range from nanometers to 25 mm. These cover a large portion of the engineered material test requirements, as shown in Fig. 2.
- *Acceleration and frequency:* The high motor forces and the low magnet mass enable accelerations up to 1500 m/sec$^2$, frequencies over 400 Hz, and velocities greater than 3 m/sec.
- *Precision:* The excellent dynamic performance coupled with the frictionless flexure suspension provide exceptional fidelity and precision.
- *Efficiency:* The linear motor is highly energy efficient, since electrical energy is directly proportional to the required force. No air or oil pressure source is required, and no energy is lost to mechanical friction.
- *Durability:* With no frictional wear in seals or bearings, and no moving parts or flying leads, the linear motor has demonstrated excellent durability, with over 15 billion cycles without a failure or main-

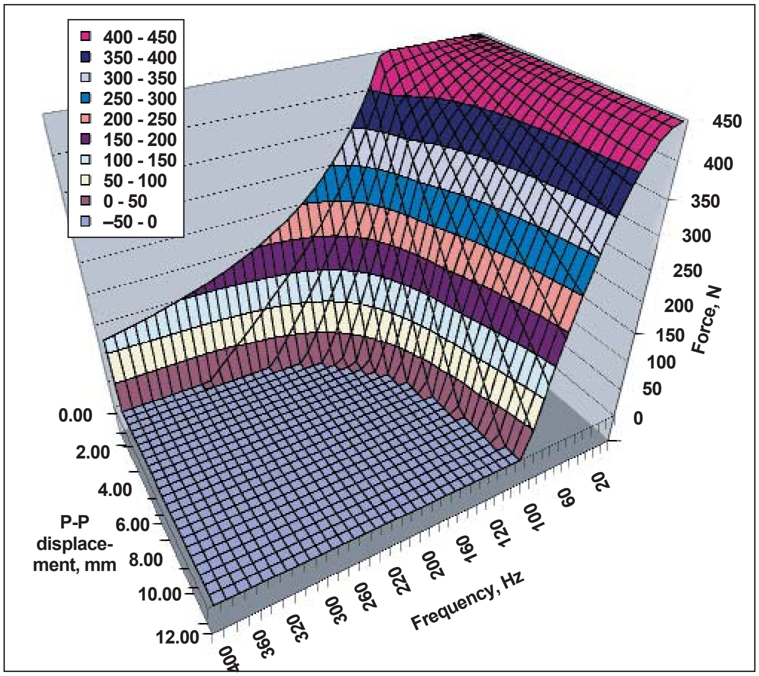

*Fig. 2 — Graph shows the sinusoidal performance of the ELF 3230 as a function of displacement and frequency. Full dynamic displacement of 12.5 mm is available well past 50 Hz with significant applied force. Significant displacement and force are available to frequencies in excess of 400 Hz.*

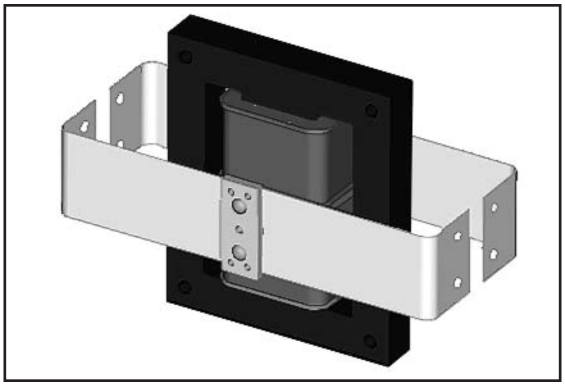

*Fig. 3 – Flexure assembly of moving-magnet motor.*

tenance. In fact, no scheduled maintenance is required.

## Flexure suspension

To keep the performance of the motor optimal, the gap between the magnet and core must be very small compared to the thickness of the magnet. The mechanical suspension serves a number of important functions. First, the suspension allows the magnet to move along the required axial path with minimal resistance. Second, the suspension keeps the magnet from crashing against the face of the core. Any contact with the core would produce deleterious friction and nonlinear behavior of the motor.

To meet these requirements, a low-mass flexure suspension with no friction, infinite fatigue life, high lateral stiffness, and low axial stiffness was developed. Figure 3 shows a simplified view of the flexural suspension of the moving magnet motor. The suspension is fabricated with a special stainless steel alloy that has exceptional fatigue properties, and has proven effective to more than 15 billion cycles.

A side benefit of the flexure design is that the flexure resists forces in the lateral and torsional directions of the main axis. The result is that multiaxis testing of specimens is a simple matter. Furthermore, multiple linear and torsional motors can be mounted on the same instrument for multi-axis applications. The precision of the linear motor allows testing at frequencies as low as 0.00001 Hz (approximately one cycle per day).

## Wire and foil testing

The forces required to test wire samples and thin foils can vary from nanonewtons to over 500 N. Displacements can range from microns to many millimeters, depending on the material, gage length, and strain level.

The following is an example of a low-force fatigue test designed to explore the fatigue limit of a wire sample. The test was run at 70 Hz to reduce the test time by taking advantage of the linear elastic

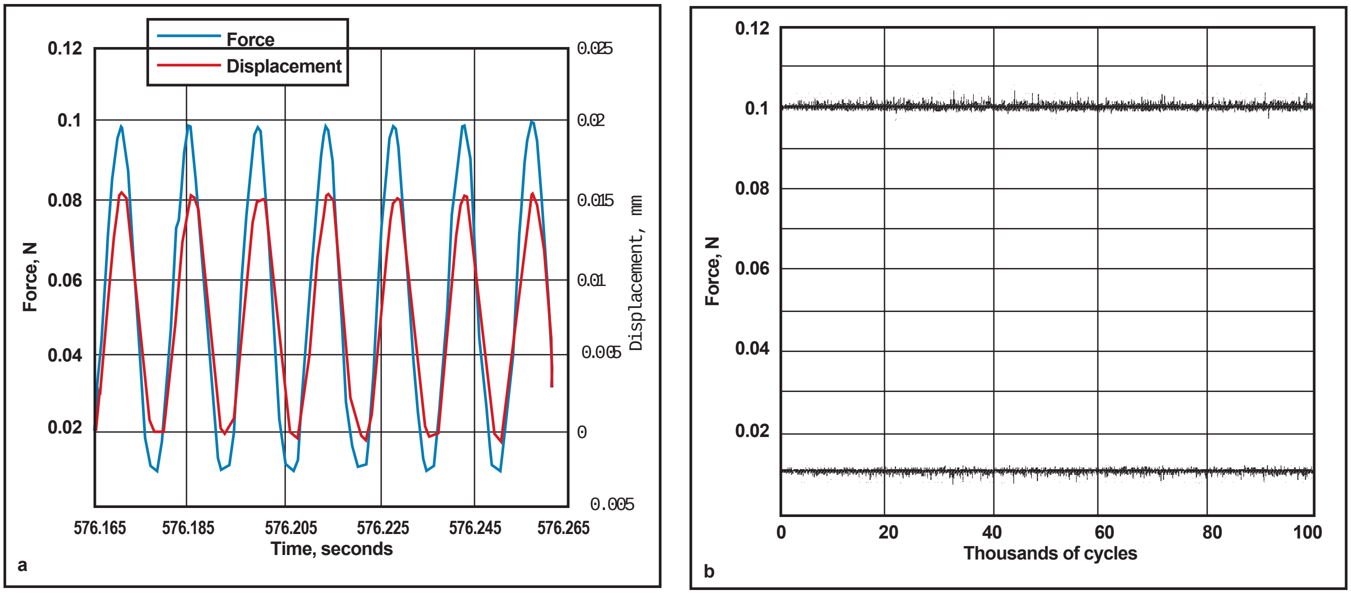

*Fig. 4 — (a) High-fidelity, low-force fatigue data at 70 Hz, 0.01 to 0.1 N. Standard deviation of the maximum and minimum controlled force per cycle was less than 0.0006 N. (b) This is an example of the force control capabilities of the linear motor. Peak and valley fatigue data are shown at 70 Hz, 0.01 to 0.1 newtons*

### *Fatigue testing technologies*

| Technology | Characteristics |
|---|---|
| Rotating-bending systems | Inexpensive to purchase<br>Bearings require maintenance<br>Constant amplitude, fully reversed, stress-controlled testing only |
| Electromechanical systems | Inexpensive to purchase<br>Low frequency only<br>Subject to bearing friction and backlash |
| Voice coil systems | Very large and expensive for high force applications<br>Typically limited range of dynamic displacements |
| Servo-hydraulic systems | Well-suited to traditional fatigue and fracture work<br>Expensive to operate and maintain<br>Difficult to use in the low force applications |
| Bose Linear motor systems | Well-suited to fatigue and fracture mechanics of engineered materials<br>Energy-efficient, with no scheduled maintenance<br>Optimized for low to medium force testing |

*The study examined how the crack interacts with the microstructure to characterize the toughening mechanisms in bone.*

behavior of the metallic material. The system is capable of a maximum force of 225 N and a frequency range from static to over 400 Hz. A 2.50 N force transducer was used to optimize the resolution of force feedback and control.

Figure 4a depicts timed data from a fatigue test from 0.01 to 0.1 N at 70 Hz. Figure 4b is peak and valley data from the same test. The standard deviation of the maximum and minimum controlled force per cycle, was less than 0.0006 N for the 100,000 cycles of data collected.

## Crack growth in small samples

Fatigue crack growth measurements in small specimens are required when sample material is limited or size effects are critical. The data illustrated in Fig. 5a and 5b offer an example of measurements taken by Dr. Dwayne Arola's group at the University of Maryland, Baltimore. The Enduratec ElectroForce (ELF) 3220 test system had a maximum load capacity of 225 N and sensitivity of ±0.01 N. The study's objective was to determine the fracture and direction-related properties of dentin, to lower the rates of fracture in restored teeth.

The specimens were subjected to a maximum wedge load (*P*) between 30 and 50 N, and a cyclic stress ratio of 0.1. The frequency of loading ranged between 2 and 5 Hz. The fatigue crack growth rate was estimated from crack length measurements conducted after specific intervals of wedge loading. The expected crack path was accentuated with silver nitrate to heighten contrast between the crack and dentin, and the crack length was measured through visual observation by a scaled optical microscope (20X).

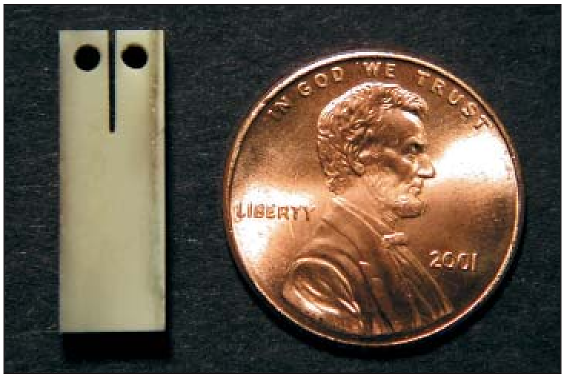

*Fig. 5a — Small crack growth sample.*

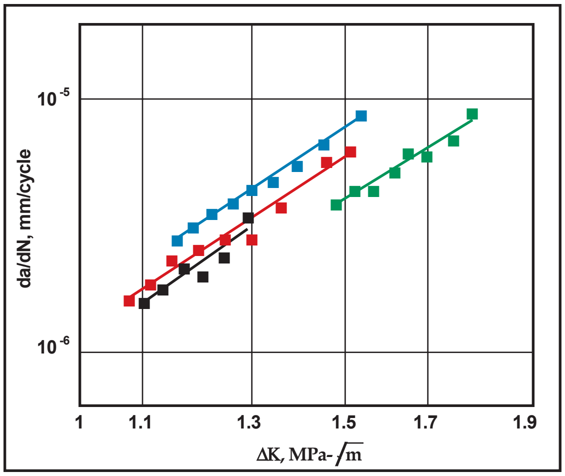

*Fig. 5b — Small specimen crack growth data.*

## Fracture of bone

In studies coordinated by Dr. Robert Ritchie at the University of California, Berkeley, the ELF 3220 test system was chosen to evaluate the fracture properties of human bone. Specifically, novel double-notched, four-point bend samples were tested to discern whether fracture in bone is stress-controlled or strain-controlled. Three-point bend samples were selected to measure the fracture toughness as a function of orientation. The study examined how the crack interacts with the microstructure to characterize the toughening mechanisms in bone. All testing was conducted at ambient temperature on an ELF 3200 series test instrument using the standard system transducers.

Figure 6 shows typical data from a crack that was grown from a rounded notch in a three-point bend specimen to a specified length between 1 and 1.5 mm. The "measured" compliance of this crack was then determined by monitoring the load-line displacement as a function of applied bending load. This was then compared to the "theoretical" compliance for a traction-free crack of identical length in this geometry.

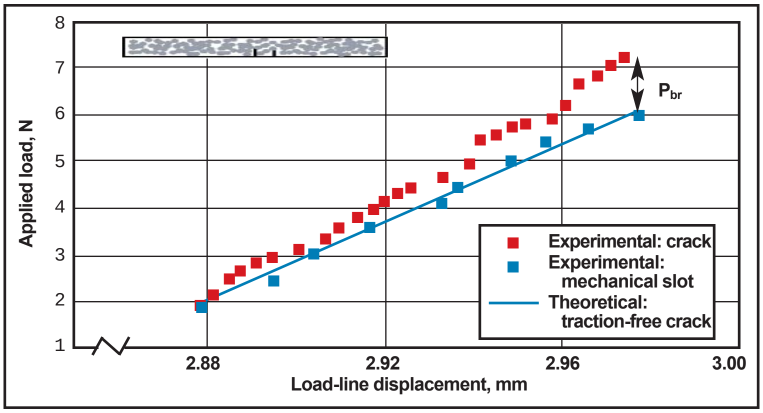

*Fig. 6— Example of compliance measurements.*

To check the veracity of the theoretical estimate for the case of bone, the wake of the crack was machined out with a slow-speed diamond saw to achieve a nominally traction-free "crack" of the same length, and its compliance was measured at increasing "crack" lengths.

Figure 7 is a highly magnified image showing crack bridging by collagen fibrils in the "anti-plane longitudinal" direction of the bone. Results of this and similar analyses show that the performance range of the new test systems permits testing from static to frequencies in excess of 400 Hz, with excellent reproduction of sinusoidal and real-world stress or strain test profiles.

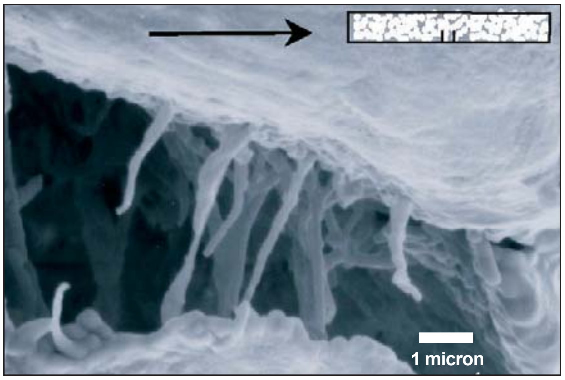

*Fig. 7 — High magnification micrograph showing crack bridging in bone.*

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**Acknowledgements**

Special thanks to the University of Maryland, Baltimore, and the University of California, Berkeley, for permission to reprint their experimental data and to the Georgia Institute of Technology for the nylon fiber samples, and North Carolina State University for the fabric samples used to create the data presented in this paper.