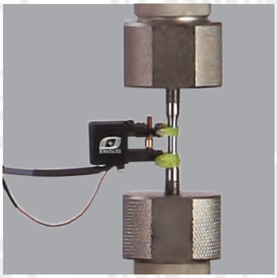
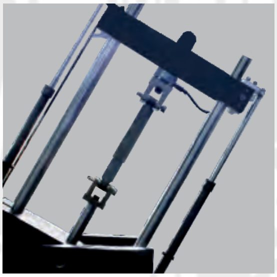
Materials and Structural Testing

The Knowhow and "Know Why"





This document is about 25 years' journey of BISS R&D in the development of servo controlled test systems to meet the various materials, structural and component testing demands of researchers and industries.

R. Sunder

BISS


CRAFTED IN INDIA
BISS

डॉ समिर वी कामत
विशिष्ट वैज्ञानिक एवं
महानिदेशक (एनएस एवं एम)

Dr Samir V Kamat
Distinguished Scientist &
Director General (NS & M)

सत्यमेव जयते

स्वच्छ भारत
एक कदम स्वच्छता की ओर

रक्षा मंत्रालय
MINISTRY OF DEFENCE
रक्षा अनुसंधान तथा विकास संगठन
DEFENCE RESEARCH & DEVELOPMENT ORGANISATION

Foreword

Materials and structural testing plays a very important role during new material development, in generation of reliable material properties data for use in design of structures as well as in ensuring safety and reliability of structures in application.

Enough literature, both in terms of books and research papers, is available on how one can measure mechanical properties of materials experimentally. On the contrary, there is hardly any published work describing the various test systems for testing materials and structures; and even these rarely touch upon the 'know why' aspect of testing which is as important, if not more, as the knowhow. Having spent the better part of my career studying the mechanical and fracture behaviour of advanced materials for various defence applications and struggling to find the appropriate tests and test systems to qualify the materials for the required application, this book's content has a special place in my heart.

The BISS team led admirably by Dr. Sunder, a good friend and a very accomplished research scientist himself, have very succinctly put together details of what it takes to perform different types of mechanical tests including the elusive 'know why'. They have also devoted a whole chapter to the test system of the future which is linked to the internet and is likely to open up new horizons in collaborative experiments, laboratory management and technical support. In addition, the book offers a glimpse into the journey of BISS which started as small startup in Bangalore and has now blossomed into a globally recognized brand name and leader in the Test & Measurement business that is part of Illinois Tool Works (ITW), a Fortune 500 Company.

I think that the authors can be confident that there will be many grateful readers who have gained a broader prospective of materials and structural testing because of their efforts.

SKamat

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Preface

Advances in engineered materials and their use in safety critical applications demand extensive testing in R&D. The current trend of outsourcing in manufacturing involves destructive testing at each global site to ensure consistency in quality. Liability clauses contribute to ever increasing accountability of all the links in the long supply chain from product development to usage. They impose stringent demands not only on design and manufacturing but also on compliance with standard testing practices.

As BISS celebrates its Silver Jubilee in 2017, its technology-driven team led by as many as three PhD's and a highly-motivated R&D and Engineering Group have accumulated much expertise and experience in what it takes to perform different types of mechanical tests and how these are addressed by BISS test technology. This book attempts to describe the knowhow as well as the 'know why' behind each test. It is a report of our progress over 25 years of exciting growth from a small startup to a globally recognized brand name in the Test & Measurement business that is now, part of a Fortune 500 holding, Illinois Tool Works (ITW). It is intended to serve as a record of advances and innovations in hard core engineering technology – something that is often overshadowed by the market achievements of outsourced IT and IT-enabled services that Bangalore seems to be better known for.

Having spent my own lifetime in experimental research using 'home brewed technology', it gives me great pride in noting that you, the reader, are likely to find answers to many subtle questions whose answers may not be readily found in the classical literature. In doing so, I hope you will also note the substantial intellectual and plain hands-on 'dog work' that may have been involved in coming up with reliable and commercially proven solutions to a plethora of challenges that confront the testing community. Solutions that have found their way across the world. Solutions, that bring back meaning to the more classical perception of 'engineering' and 'techies'.

In reporting cutting-edge technological advancements that any institution of national importance would have been proud of, I must acknowledge the steadfast support of extremely demanding customers, who would settle for nothing but the best. And in equal measure, I would like to place on record my sincere appreciation for the die-hard fighting attitude of my own young colleagues, who achieved so much, often, simply not accepting that some things may just be impossible. This was a partnership sometimes built on a leap of faith by customers with high expectations, matched in equal measure by the determination and commitment of the entire BISS Team. A partnership that has resulted in tens of millions of dollars of test technology serving hundreds of sites worldwide. And a partnership that established arguably, the country's largest fatigue and fracture laboratory with both ISO 17025 and Nadcap accreditations.

R. Sunder, Research Director, BISS (P) Ltd

Acknowledgement: Dr. Somayya Ammanagi, Head, R&D, meticulously collated the material in this document, including archival pictures from 25 years of BISS operations.

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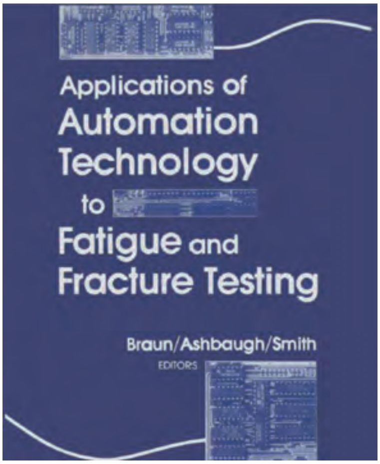
1. Controls – the Heart of it All

The control and measurement system defines both the quality and performance limits of a test system. No test system can deliver better results than what its control hardware and software permit. The very essence of the BISS team's struggle to 'claw into' the 'big league of testing' has been the continuous focus on keeping its control and measurement technology in pace with or ahead of the 'global state-of-the-art'.

The Cover (as in **Figure 1**) of the 1990 Special Technical Publication (STP) 1092 of the American Society for Testing and Materials (ASTM) devoted to Applications of Automation Technology to Fatigue and Fracture Testing carries the picture of the single board controller developed at the National Aerospace Laboratories (NAL). This was a tribute to an industry 'first' – an entire test controller (**Figure 2**) on a *single* board, including processor, memory, communications with host computer, data acquisition and control waveform generation! It was appropriately called the Intelligent Mechanical Test Controller (IMTC). 'Intelligent', because it accepted commands in English and data in engineering units. The IMTC automated the test process through a simple, noninvasive connection to existing analogue consoles that already carried the required signal conditioning modules and servo-amplifiers which were the state-of-the-art in the early 1980s.



Applications of
Automation
Technology
to
Fatigue and
Fracture Testing

Braun/Ashbaugh/Smith
EDITORS

Figure 1 Cover page of 1990 STP 1092 of ASTM (showing image of single board controller developed at NAL).

Figure 2 IMTC controller on an MTS test system at IISc (c. 1986).

Licensed to BISS in 1993, the IMTC saw changes driven by market needs. In the 1990s, software programmable signal conditioners, servo amplifier and pump control logic were added to convert the IMTC into the most compact full-fledged test system controller on the world market. Being a single board solution, it did not carry any of the internal cables or sockets and edge connectors, typical of conventional systems. This made it extremely reliable and rugged. In the nineties, servocontrol was rendered fully digital, resulting in the removal of the analogue servo-amplifier circuit and making the design even more compact.

Figure 3 2350 N-Channel Controller (c. 2001).

Year 2000 brought in a sea change to BISS design perspective. Demands grew for much greater variety of solutions, involving increase in the number of acquired measurement channels, multi-channel controls and an expanded variety of transducers, including rotary and linear encoders (**Figure 3**). The single board solution had finally outlived its relevance. Getting multiple such controllers to work together is still practiced by some 'brand names', but getting them to work reliably and do so with a high degree of synchronization and real-time processing of acquired data challenges their use and limits their potential.

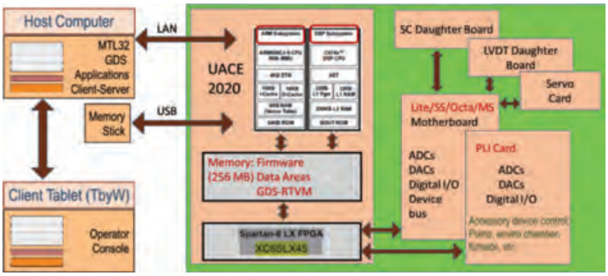


Figure 4 2370-Controller Architecture.

Backed by two decades of experience in test controls, a new design emerged for a unified software solution to practically all requirements of mechanical testing and measurement. We put this software onto a Unified Architecture Controller Engine (UACE) 2020[1] (**Figure 4**). This is a single, all-digital board that contains a powerful multi core digital signal processor (DSP), large memory and a high capacity field programmable gate array (FPGA) that serves as the interface with a variety of motherboards that contain the required hybrid electronics to handle controls and measurement of different levels of complexity. Thus, the UACE 2020 serves as a common digital platform for absolutely all BISS systems. The Lite version is intended for low-end single channel systems, including retrofit of legacy test systems. The 'SS' handles high performance control and measurement, clocking up to 12 kHz of loop update and 8-channel data acquisition, the Octa[2] as the name suggests, caters to 8 control channels and up to 24

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[1] In the belief that it reflects 20-20 vision and in the expectation, that it would be good beyond year 2020.

[2] The 2370 Octa controller's motherboard specifications were formulated to suit the entire range of test systems produced by Instron-TGT, a Division devoted to serving the needs of tissue growth and medical device testing that later was absorbed by BISS and now covers all Low Force applications. These include axial, axial-torsion and planar biaxial test systems.

channels of data acquisition.The octa is capable of burst data acquisition up to 100 kHz. Finally, the ‘MS’ is the top end controller designed to handle 32 channels of control and up to 80 channels of data acquisition. The MS essentially combines the resources of multi-actuator control and multiple channels of data acquisition that are required in structural testing.

The UACE 2020 ‘thinks’ ‘n-channel’ and ‘n-station’. It can work with multiple independent test systems, each with one or more channels of control.

Precision and resolution in control and measurement determine the reproducibility of test results, which is the objective of every standard test practice. In experiments associated with fundamental research, even higher complexity of testing and quality of measurement may be required to study the more subtle and perhaps, hitherto unknown elements of material behavior that are worthy of a research paper, discovery or invention. The focus of BISS system design has been on this objective

1.1. Performance and quality of controls

As an assurance of both precision and performance in controls, all BISS control systems implement as many as four levels of servo-control on each control channel. The lowest level of control is exercised by the multi-component servo-control algorithm operating at the frequency of digital loop update. This includes conventional three-component PID control, and, several more components *including proprietary patented elements* that are incorporated to handle practically every type of drive and every possible ‘idiosyncrasy’ that a test object can exhibit, from variable stiffness and damping response, right down to highly unpredictable instantaneous changes in behavior. This primary loop is overseen by a choice of three outer loops. The first outer loop is adaptive control used in constant amplitude loading that quickly achieves required mean and amplitude to within 0.5% of set values, even if the system may not be perfectly tuned. The second outer loop is useful in durability testing under pseudo-random load sequences where it is important to achieve the assigned peaks and valleys flowing in a random sequence. This scheme involves the continuous update of a three-dimensional error and correction matrix that effectively ‘learns’ about and proceeds to correct specimen response to individual load (or stroke / strain) excursions, so that, in a matter of minutes, the control and feedback are seen to match to perfection. This is a continuous process and therefore responds to any gradual change in specimen response as in the case of fatigue crack growth. The development of these two technologies is described in ASTM Special Technical Publications (*ASTM STPs 1006, 1092*). The third outer loop is designed for random time-histories as in shake table applications (*Current Science, Vol 91, No2, 2006*). In this case, the adaptive process is iterative.

High performance actuators of large force rating are often used in automotive and structural testing. They rely on high flow servovalves of multi-stage design, where a conventional servo-valve controls the position of the spool on a much larger valve, typically capable of handling flow rates as high as 2000 LPM, i.e., as much as 2 tons of oil a minute! Conventional solutions involve the use of analog servo-control of the main spool of such valves with a suitable electronic module provided for the purpose. In this configuration, the servo output from the control system serves as the 'Set Point' for the 'desired' position of the main spool that in turn will set the flow rate through the main valve to one or the other port on the actuator. Thus, we essentially have a servo-loop within a servo-loop. By harnessing the energy in the hydraulic system to also control the main spool position, multi-stage servo-valves allow servo-control using the same small currents or voltage signal that is used in much smaller systems.

It would not be unrealistic to imagine a servo-valve control flow rate of the magnitude even seen over Niagara Falls, using the same small current signal. This essentially is the same know-how that drives the popular dancing fountains at attractions around the world. However, the response time as well as the fidelity of response of multistage valves theoretically cannot match that of a single-stage servo-valve because of the inherent lag and hysteresis that accumulates with each stage. To alleviate this problem, BISS R&D embarked on a unification of the digital servo-control algorithm **(Figure 5)** built into controllers and totally eliminating all analogue servo electronics as a requirement in multi-stage valves. Being 'n'-channel by design, the algorithm was configured to operate in 'cascaded' configuration whereby, each stage of a multi-stage servo-valve is treated as an independent control channel, except, that at any instant, the servo-output of the previous stage is treated as Set-Point for the next one. The challenge addressed by this solution is design of the mathematics behind servo-control in a manner that makes it extremely simple for a technician to wire the controls and then tune an actuator with a multi-stage valve. This makes BISS controllers compatible with any type of servo-valve used by industry right up to multi-stage servolvalves rated to thousands of litres per minute. The development was validated during modernization of the high-performance MTS structural test actuators **(Figure 6)** at the National Technical University, (NTU) Singapore, where multi-stage valves are installed. The upgrade meets or exceeds original manufacturer performance specification. The retrofit has been serving NTU research requirements.

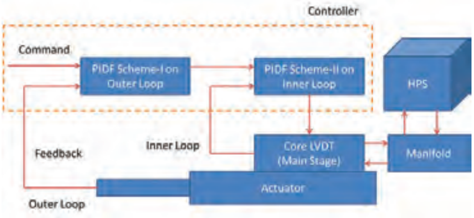


Figure 5 Servo control algorithm for a three-stage servo valve.

Figure 6 High performance actuators (2000kN), at NTU Singapore, retrofitted with BiSS 2370 controller

1.2. Measurement Quality

BISS pioneered the adaptation of several high-resolution data samplers to materials testing, riding on advances in hybrid single-rail electronics developed for biomedical applications. For over 15 years, BISS controllers have incorporated 24-bit analogue-to-digital converters whose resolution by design exceeds *ppm* threshold. Given the intrinsic noise of analogue signals, this worsens to about one part in half a million by over sampling, though individual readouts may vary by about 0.01%. The appearance of high resolution and high linearity digital encoders has further improved the quality of measurement with measurement resolution effectively determined by transducer resolution alone. As mentioned elsewhere, actuator stroke measurement on BISS materials test systems is *guaranteed at 0.1 micron, which amounts to 1 ppm on a 100 mm stroke*! The new digital load cell developed at BISS (patent pending) is expected to deliver readout quality that *cannot be matched by any conventional solution by way of strain bridge or piezo-electric designs* that are the current state-of-the-art. Together with digital extensometers, the new digital transducer technology permits Modulus measurements that are at least 3-5 times better than what is possible using conventional load cells and extensometers.

1.3. Safety Limit Interlocks

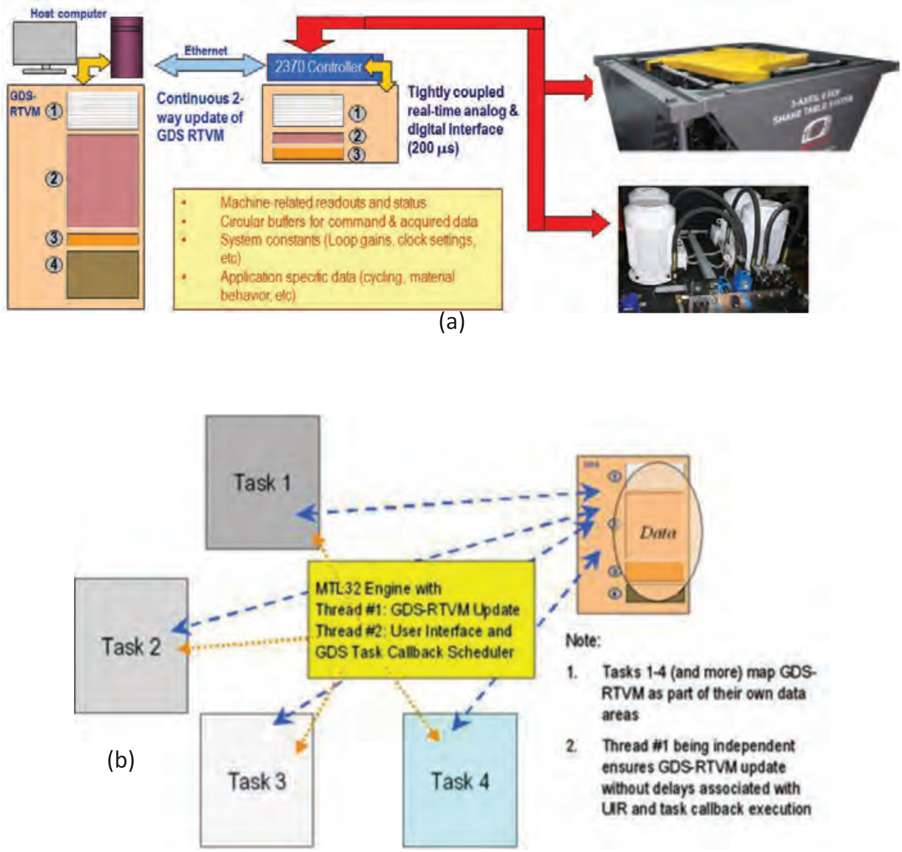
The test process, like any other control and measurement process, demands the ability to ensure safety and protection. BISS controllers provide for three parameters to judge safety on each and every feedback channel, each with a choice of three options of immediate action. The three parameters are upper and lower limit and also absolute error if the given channel serves as feedback to the control loop. In the event, any armed limit is crossed, the test will be stopped, power tripped and/or control mode switched, depending on selected options. This action will be triggered within a millisecond, but the actual response seen will depend on the type of drive in use. Hydraulics for example typically responds within 10 to 40 ms. Safety limit interlocks are quintessential to protect the integrity of the test setup and also to avoid damage or injury. A simple example is that of a gripping assembly located inside a furnace that can damage the furnace if pulled beyond a point by the actuator.

The evolution of a unified digital platform means much to the BISS customer base and means practically everything to both BISS system as well as application developers. Customers can be quickly supplied with a solution for practically any test and measurement requirement. Digital components are not expensive and therefore the customer is not overburdened by the cost of ‘excess processing power’ of the controller. On the other hand, the number and type of hybrid electronics modules can be configured to specific customer requirement, therefore, the customer seldom needs to buy into more than what is necessary to suit his requirement. Importantly, a unified controller architecture means support personnel can handle the entire range of BISS equipment with equal ease. This translates to more efficient and cost effective customer support. The latter is also assisted by modular electronics and the associated common set of spares for the entire range of BISS controllers (**Figure 7)**.

Figure 7 Different versions of 2370-Controller (left to right: Lite, SS, OCTA & MS).

Over the past five years, the UACE 2020 'engine' has proven itself to be a truly universal hardware and software platform. The variety of applications it currently serves is practically unmatched in the global market. Systems operating worldwide on this platform range from universal testing machines to axial-torsion and planar biaxial test systems with four servo-actuators, from multi-channel structural test rigs to multi-station test laboratories, from single axis shake tables to complex 8-actuator, 3-axis, 6 degree-of-freedom earthquake simulators, from multi-axis bushing testers to five-axis friction stir welders! To realise that *absolutely the same basic code sits on all these systems, but is set to perform vastly different tasks by the mere click of the mouse* may demand a certain stretch of imagination. But that indeed happens to be the case. Perhaps, the editors of ASTM STP 1092 did imagine back in 1990, that their choice for the cover would go some distance in time to come……

The universality of BISS controller architecture is matched in equal measure by the MTL32 application platform on the PC that serves as an intelligent and powerful 'server' for an ever-growing number of test applications. It does so in the *unique and proprietary Global Data Sharing (GDS) environment* that has been implemented in both 32 and 64-bit Windows (**Figure 8**). MTL32 essentially frees test applications from the demanding and cumbersome 'real-time' world of test and measurement. It does so by taking upon itself, the entire responsibility of sequencing commands to the controller in a strictly time-bound fashion, while also doing an enormous amount of sorting and processing the incoming stream of readouts in a manner that can be easily 'digested' by application programs to execute the required test procedure. Some test procedures may involve a number of independent tasks that need to be performed, some, customized for a particular requirement or customer need. This is where the GDS environment comes into its own. *It allows the simultaneous execution of multiple tasks related to an ongoing test, without in any manner slowing down or interrupting one another.* These can include third party and end-user applications written on practically any software platform including Visual C++, C#, Visual Basic, Delphi, LabVIEW, or even as XL-Macros! All these features together render unmatched power and flexibility to the hardware and software at the heart of each test system.



Note:

1. Tasks 1-4 (and more) map GDS-RTVM as part of their own data areas
2. Thread #1 being independent ensures GDS-RTVM update without delays associated with UIR and task callback execution

Figure 8 Global Data Sharing Real-Time Virtual Machine (GDS-RTVM) implemented on: (a) BiSS 2350, 2360 and 2370 Series Control Systems for single and multi-channel control and data acquisition; (b) front-end (host computer) to operate in concurrent multi-tasking mode.

2. The Test System in the Internet of Things

The Internet has revolutionized movement of information and with it, there has been a quantum jump in productivity as professionals are able to translate information into decisions and decisions into action with increasing ease and rapidity. The latest stage in this revolution by way of 'The Internet of Things'. More and more people are finding they can keep track of what is happening at home while at work or on the move. Not only that, they are also able to take decisions and translate them into action, for example, switch on the oven or the washing machine.

The Silver Jubilee Year at BISS marks the entry of the BISS Test System into the Internet of Things – *another industry first.*This is the culmination of over four years of R&D effort across several levels of hardware and software:

i. Before planes could be totally flown by autopilot, even remotely, they first needed to be converted into 'Fly-by-Wire' systems, i.e., every operation that a pilot can do needed to be implemented exclusively through wiring and signals, rather than through manually activated mechanical switches, valves, levers, etc. In much the same way, BISS test systems needed to be converted into 'Test-by-Wire' systems. Specially designed electronic circuits and protocols were developed to enable complete 'programmatic' control over the test system and all its accessories. This was called the Programmable Logic Interface (PLI). The PLI is wired to control the pump, the cross-head lifts and clamps, grips, furnace, chambers, etc. Most new BISS test systems are equipped with PLI cards along with all the associated interface hardware.

ii The smartphone is today by far the most widely used instrument of communication. In the scheme of the Internet of Things, the smartphone is likely to be the dominant source of commands going to devices and of information flowing back for display. However not all smartphones have a large enough screen for convenience of working with more complex 'Things'. That is where the somewhat larger tablet comes in handy. Even though the software will operate on most smartphones, starting 2017, all BISS test systems carry an Operator Console in the form of an Android or Windows tablet (**Figure 9**). The tablet is mounted on an ergonomically designed stand that is part of the load frame. The adjustable stand houses fully concealed wiring. In fact, a major feature of new BISS test systems is their streamlined appearance with minimum clutter of hoses and cabling.

iii The tablet Operator Console allows absolutely all system related operations from intuitive and context sensitive graphics user interface. System communication is via WiFi using fail-safe communication protocols that withstand the threat of momentary communication failure or errors in data flow. Hence the idea of 'Test-by-WiFi'. This means that the tablet can be momentarily removed from its stand and taken to any point of local operator activity, e.g., to position a structural test actuator for ease of mounting a specimen (**Figure 10)**, to verify proper specimen response on complex multi-actuator structural rigs, etc. This capability eliminates the dangers of damage and injury associated with inter-personnel miscommunications and in fact eliminates the need for multiple personnel for such purposes.

The PLI and Test-by-Wire technologies open new horizons in laboratory management, technical support, collaborative experiments and even in the business of testing services. Application software to be commercially available in 2017 includes control and monitoring packages that permit laboratory operators as well as their managers keep track in real-time of tests running on individual test systems and if required, gain control of them. This is possible both via office networks as well as the Internet. Customers needing tech support can now 'share' their test system with tech support personnel who may be remotely located. Scientists at different sites collaborating in experimental research can simultaneously view and review an ongoing test to accelerate their work and eliminate delays around iterations. Finally, customers outsourcing testing services can enforce total confidentiality of their test details as well as results by running the relevant test application software on their own computer systems while the test itself may be outsourced. Such client software operates in much the same manner as the same application on the test systems host computer, but does so remotely, with the host computer operating merely as a 'go-between' for commands and data. *'Test-by-Net' is thus the ultimate in connectivity. It opens the doors to globally outsourced testing services, collaborative experiments and remote techsupport.* A customer can exercise his 'virtual presence' across all those locations where his tests are running. All this was made possible thanks to the very architecture of Global Data Sharing (GDS) that is intrinsic to BISS systems.

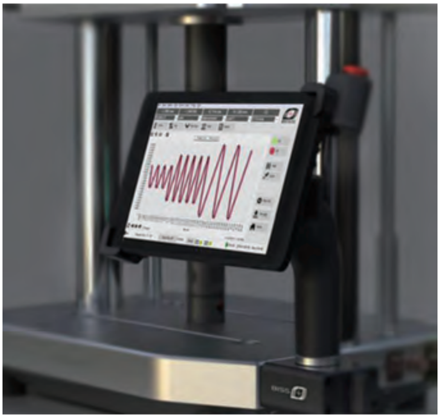


Figure 9 Android Tabled based PLI mounted on load frame of a test system.

Displacement
-0.225 mm
Load
0.229 kN
Strain 1
1.357 mm

System is ready to mount the specimen

Figure 10 PLI App panel for adjusting actuator position for ease of specimen mounting.

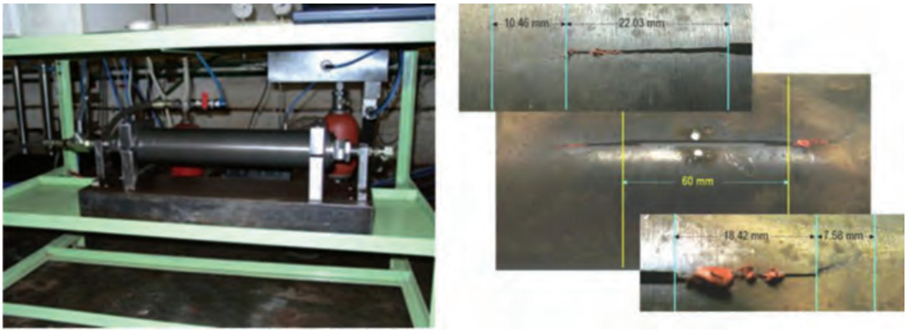
3. Some Special Purpose Systems

The advent of digital and hybrid electronics in late 1960's opened the door to automation of both drives as well as measurement through software. The ultimate is reflected in fully automated factories that do not rely on the human factor in real-time process control, with due consideration to both quality as well as safety. Each industrial process is unique in more than one way. Laboratory processes are no different. Customised special purpose systems (SPS) are not an exception. Their design and development hinges on the one hand on engineering the required electro-mechanical components and on the other, on the ability of the control and measurement system to harness these resources to serve as an effective solution to required functionality and performance.

BISS control systems owe their success to the wide variety of applications targeted by partners in industry as well as in cutting edge spheres of science and technology. Described below are some examples to highlight what was involved. Common to all of them was the application of the 2370 Series Controller and customized software built around the Global Data Sharing (GDS) architecture.

3.1. Burst Test Rig for Pressure Vessels

The economics and safety of nuclear power reactors hinges on the structural integrity of their components. Their operational principle may be simple and obvious, but the 'Devil is in the details'. Thus, the simple part is about heat from fission being transferred to water to have the steam drive the power generators. To avoid radiation into the environment, heat transfer is through an intermediate closed loop of circulating water that needs to be kept at a high pressure of 115 atm to prevent it from boiling when heated to 300 degrees by the nuclear fuel elements. Obviously, life of the nuclear power reactor will in part be restricted by the that of the pipes carrying this water. Even though the pipes are made of expensive and extremely ductile and resilient rare earth metals such as Zirconium and Niobium, sustained usage can lead to their embrittlement and cracking through slow but steady reaction with water. The only sure way of assessing the condition of such pipes is to check them for residual burst strength in the presence of a through crack. A through crack will leak and this is a sure way of detecting damage and safely shutting down the reactor. However, if it bursts in the process, the consequences would be catastrophic. BISS R&D developed and supplied to the Department of Atomic Energy, a Special Purpose Test System (**Figure 11**) to qualify sections of irradiated pipes for their ability 'to leak before break'. Several technologies, processes, hardware and software were developed to perform such tests to challenging requirements. The pipes would be irradiated, having served decades of usage, therefore the entire process of specimen preparation and testing needed to be handled 'remotely'. A slit representing a crack initiator needed to be cut, then sealed from the inside in a manner that would allow the crack to 'open' and grow in fatigue to simulate a natural crack, but at the same time, not allow pressurized water to leak, even at high temperature and pressure – highly contradictory requirements! Pipe butt sealing arrangements were specially designed to eliminate axial load on the pipe – so as to restrict loading condition to hoop stress only. Hardware and software were developed to cycle the internal pressure to grow the crack in fatigue to the required length in much the same manner is performed on simple laboratory coupons following standard pre-cracking practice per ASTM E1820. To make this possible, a special COD gauge was developed to measure specimen compliance across the crack. As a result, for the first time ever, it became possible to perform a J1c test on a pressure vessel with a through crack, subject to internal pressure and at elevated temperature! The SPS has served the customer in assessing the structural integrity of ageing nuclear power reactors.



(a) (b)

Figure 11 Pipe burst test system: (a) test setup; (b) close-up of burst pipe.

3.2. Launch Vehicle Damper Tester

The new generation GSLV launch vehicles used by the Indian Space Programme to put heavy communication satellites into geostationary orbit use multiple strap-on boosters to the main booster on the first stage. The thrust oscillation from individual boosters can exceed tens of tons. The associated vibrations can threaten not only the delicate insides of the communication satellite payload but also the structural integrity of the complex assembly being shot into space. Specially designed composite dampers are used for vibration isolation and are required to be tested for performance. A biaxial SPS (**Figure 12**) was specially designed for this purpose. The complexity and criticality of the SPS can be judged by the 18-month design and review by a team of experienced space engineers and BISS R&D that preceded the actual manufacture of the system. *The result was the most powerful test system operational in the country – of close to one megawatt rating*, capable of applying 100 tons in one direction and 60 tons dynamic at over 50 Hz in the other direction to test the damper under conditions of actual usage. High performance precision digital servo-control delivers high force, high precision oscillations with micron accuracy by exercising up to *2000 liters per minute* of high pressure hydraulic flow into the servo-actuator, an achievement unsurpassed in this part of the world. This small, but demanding contribution brings as much pride to the BISS Team as the success of our Space Programme brings to our entire country.

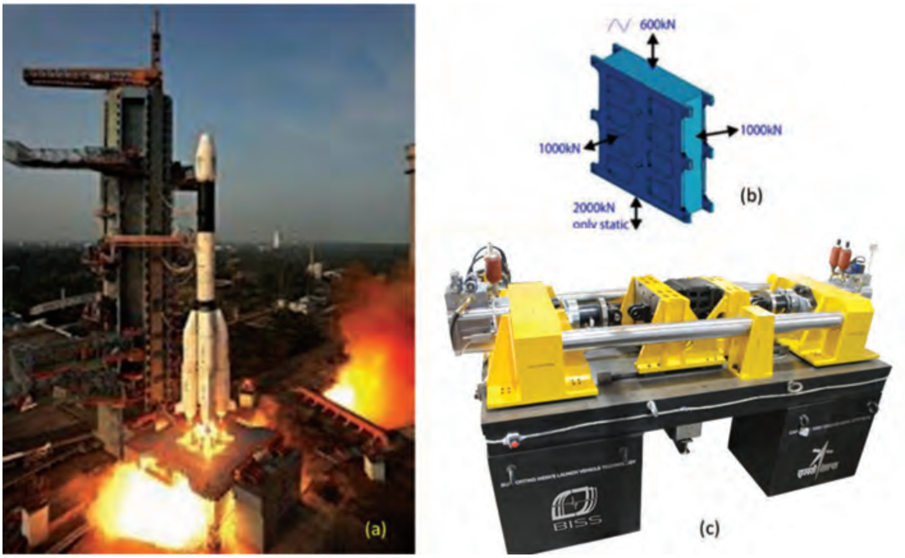


Figure 12 A test system for multilayered elastomeric modules (MEMS) test system: (a) Indian *GSLV; (b) a sample MEMS; and (c) biaxial test system developed by BISS for testing MEMS.*

3.3. Fretting Wear Test System

One of the devious ways in which operating conditions can induce premature failure is fretting fatigue. When two metal surfaces are in contact and experience continuous, barely discernible relative movement, the expected result is wear of one or both surfaces. However, if the associated bearing forces are sufficiently high, wear can be accompanied, or at times, even be replaced by micro-cracking at the surface that can proceed to grow to catastrophic proportions. This is a serious problem in the industry, particularly when vibrating components or those seeing thermally induced relative movement continue to operate over prolonged duration. The mechanism of fretting is sensitive to environment. Studying the phenomenon demands a test system capable of applying controlled high frequency oscillations (as high as 100 Hz or more) between two surfaces along one axis of precisely controlled magnitude that can be of the order of a few microns, while simultaneously applying a controlled bearing force between the two surfaces. Such a test system was developed by BISS R&D for Indian

Institute of Science **(Figure 13).** The challenge addressed by the development effort centered around precise control of very small relative displacements occurring under large bearing loads. This is required to obtain reproducible results in testing for fretting fatigue in a controlled environment including low vacuum.

Figure 13 High Frequency Fretting Wear Test at IISc, Bangalore.

3.4. Friction Stir Welding (FSW) System

With the expiry of patent protection for the Friction Stir Welding (FSW) process interest has grown in different ways of implementing it. As a consequence of collaborative research in the field between IISc and BISS scientists, a fully automated 5-axis FSW SPS (**Figure 14**) was developed that has found several users. Several technological challenges were addressed in the process. The first pertains to the FSW process itself that involves heating by rotational friction of the tool bearing against the interface of two adjoining metal parts leading to their 'plastification' to a point that the two edges can mechanically 'blend' to form a homogenous and strong welded joint. This demands precision control of bearing force, rate and depth of tool penetration, associated tool orientation and rotational speed, required to enforce the FSW process. Another challenge is to enforce triaxial tool movement to precisely follow the required 3D contour that represents the shape of the actual parts being welded into one. This contour in turn needs to be derived from CAD drawings of the final object being designed as a measure of easing the move from the drawing boards to hard metal. Finally, the entire system needs to be proven to work the required mix of metals to be welded and the shape and size of objects to be created via the FSW process. Getting the BISS 2370 Controller to serve as the engine for the FSW SPS served as a test of its versatility as a world class process controller. Getting the two to serve the interest of scientists and engineers in the field serves as a monument to the spirit of collaboration and partnerships between the BISS Team and academia.

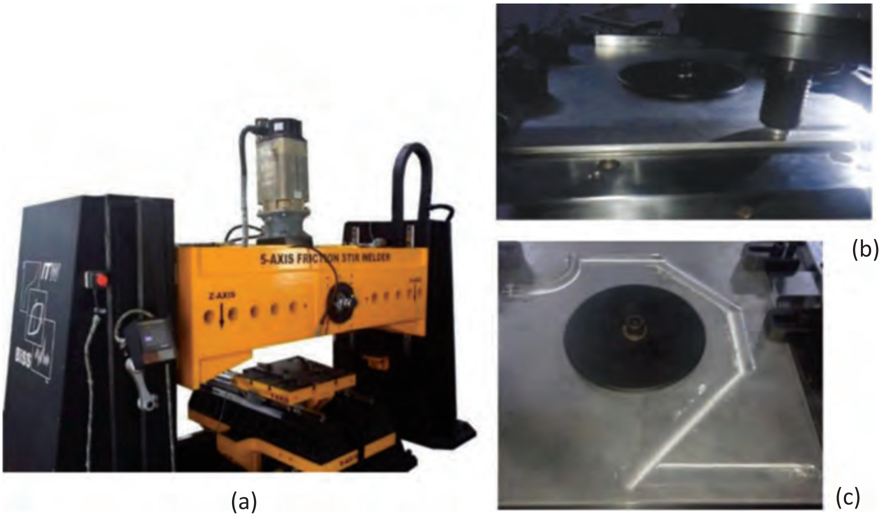
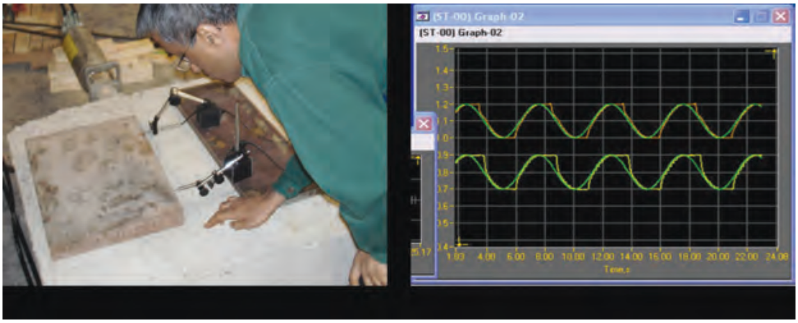


Figure 14 Friction Stir Welding: (a) FSW system at IISc; (b) in the process of FSW on a sample; (c) after completion of FSW on the sample.

3.5. Earthquake Resistance of Reinforced Concrete

A unique SPS application implemented at Stork Inc – a premier test lab in Minneapolis, USA involves testing the residual strength and durability of anchors screwed into reinforced concrete slabs under conditions simulating earthquakes (**Figure 15**). The requirement is for anchors to withstand earthquakes even if a through crack runs through the concrete slab, thereby weakening the retention force on the anchor. Getting a natural crack to form and grow in a concrete slab using conventional technology is extremely complex and expensive. It involves pulling all individual re-bars simultaneously in fatigue. BISS R&D adapted conventional splitters to servo control and a three channel SPS solution was developed for the purpose that has served Stork for many years.

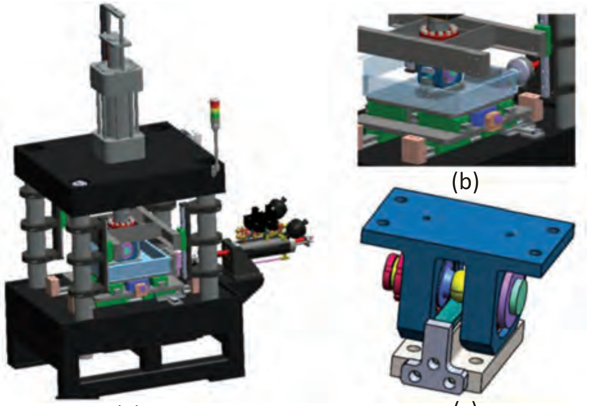


(a) (b)

Figure 15 Testing for strength and durability of concrete slabs: (a) crack (in concrete slab) width controlled test; (b) quality of waveform fidelity in crack opening closing control.

3.6. Bearing Test Rig

A unique biaxial SPS was recently developed for GE Global Research to carry fatigue testing of a segment (≤ 100) of the large bearing tracks on wind turbines. The system simulates the combined action of radial and traction loads that eventually lead to pitting and failure (Figure 16).



(a) (c)

Figure 16 SPS developed for GE Medical R & D for durability testing of bearing tracks on MRI systems: (a) test system; (b) close-up of load train involving fixtures and specimen; and (c) close-up specimen subjected to biaxial loading.

3.7. Biaxial Shake Tables

Customised biaxial shake tables to simulate oscillations along two instead of three planes are often required for qualification testing of structures and machines. Conventional 'brand name' solutions resort to the use of swivels on the actuators to enable rotational movement in order to accommodate biaxial oscillation. Swivels invariably add to clearances that can dilute the fidelity of reproducing low amplitude oscillation. BISS R&D was set the task of developing a biaxial shake table (**Figure 17**) with flange mounted actuators to ensure backlash free oscillations and enhanced durability of the SPS by eliminating actuator rotation. Such a table is on supply to an overseas customer involved with the development and certification of high performance structures.

Figure 17 Biaxial (vertical plane) Shake Table.

3.8. Special Purpose Rigs for Automotive Testing

The 2370 Controller allowed development at BISS R&D leading to the supply of a wide variety of test systems for the automotive industry. These include multi-channel test systems including a steering system test rig for Suzuki that simultaneously simulates actual multiple road load actions involving the two wheels and the steering column (**Figure 18**), a four poster to simulate random road load action on the four wheels of a car (**Figure 19**), a tyre test rig that simulates speeds of up to 300 kmph with measurement devices to track tyre shape in running condition (**Figure 20**), a multi-axial shake table to test durability and noise of vehicle subassemblies (**Figure 21**), a side door crush test rig that validates cabin safety in the case of an accident (**Figure 22**) and an SPS for a reputed Italian manufacturer of pulleys for automotive engines that dampen the unavoidable engine shaft angular oscillation due to the sequential firing of individual cylinders in an internal combustion engine (**Figure 23**). These pulleys transmit the torque to engine accessories and they need to be tested for both performance and durability under simulated service conditions involving both torque as well as belt tension. At the request of a Russian Technical University studying suspension systems for heavy vehicles, a unique suspension tester (**Figure 24**) was developed that reproduces road roughness conditions to excite the wheel connected through dampers to a mass simulating vehicle loading. This rig permits characterization of suspension components under simulated service conditions and is used in design and optimization studies. Also of note is an SPS developed to test the durability of pneumatic braking system on Volvo heavy vehicle axles (**Figure 25**). The system simulates actual braking force exerted on the wheel along with the inertial torque from vehicle movement.

Figure 18 Durability testing of automotive steering system

Figure 19 Four-poster test rig for dynamic testing of vehicle structure for road loads.

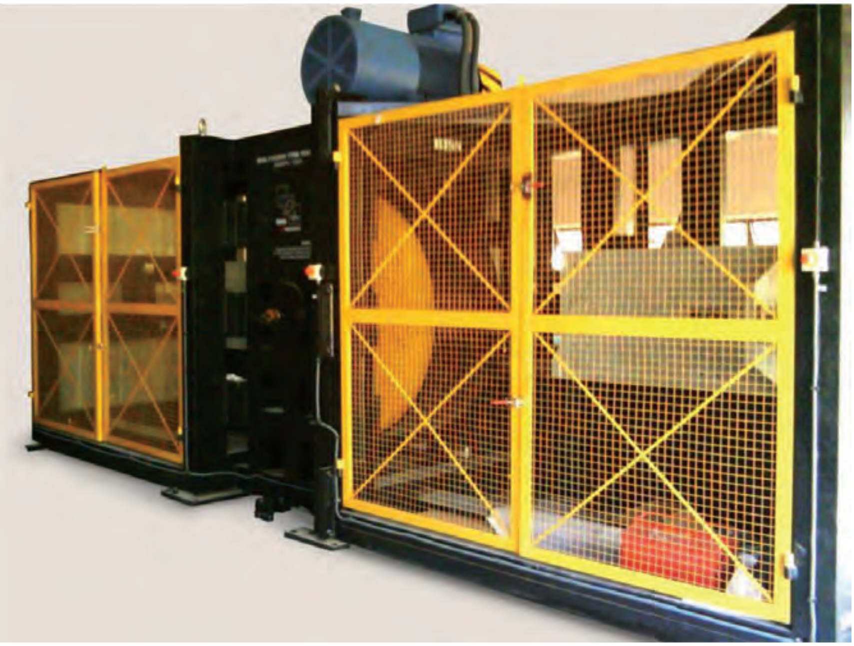


Figure 20 Tire test-rig to track tire shape during running on roads.

Figure 21 Multi-axis shaking table (MAST) for dynamic testing of automotive components under road loads.

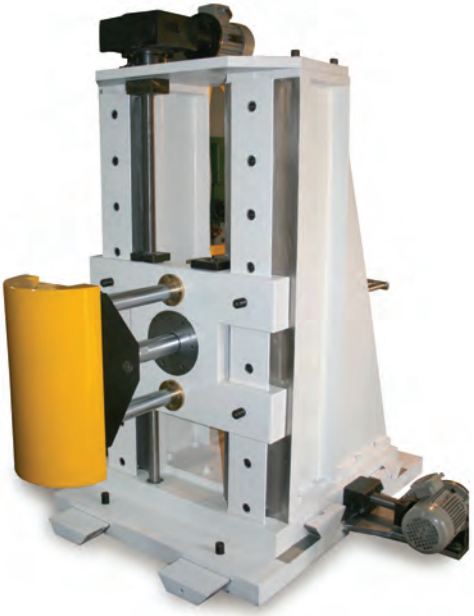


Figure 22 Side door (of a four-wheeler) crush test system.

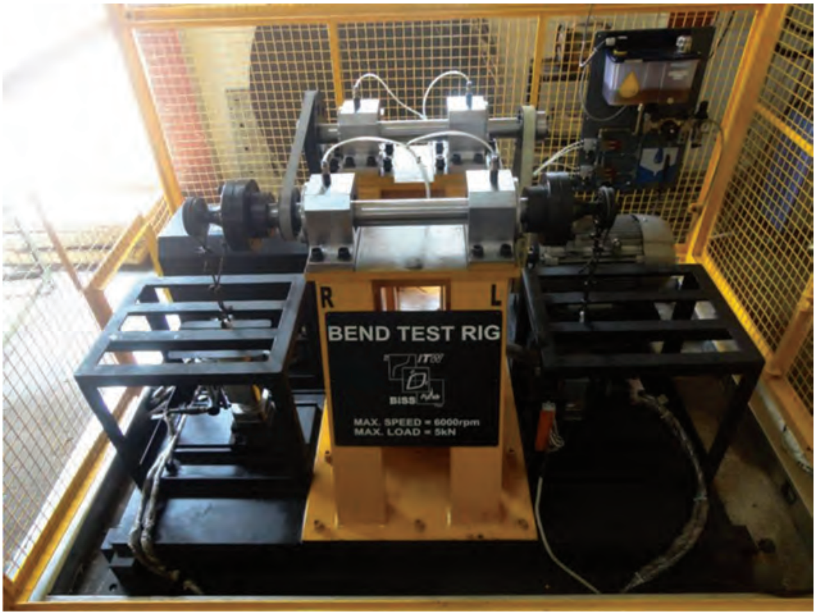


Figure 23 A system for testing dampers used in dampening the engine shaft angular oscillations

Figure 24 Suspension Tester.

Figure 25 Testing truck braking system

4. Modernization of Legacy Systems

Servo-hydraulic test systems are expensive capital equipment designed to operate for twenty to thirty years. The mechanical part of the systems can serve indefinitely. The hydraulic system contains many parts that can be readily replaced with new ones. All these seldom grow into obsolescence even over 10-15 years. However, the control system of a testing machine grows obsolete within 5-7 years, largely because it is no longer compatible with newer generation host computer hardware and software. Obsolescence also advances with many chips on the controller electronics being rendered obsolete, endangering technical support.

Fortunately, obsolescence or failure of the control system does not mean that the entire test system needs replacement. Quite to the contrary, it is the control system that to a large extent determines the quality and performance of a test and measurement system. Test systems from different manufacturers seldom differ in the manner that their basic components operate; what makes them appear different is essentially the control system.

The interface between a control system and the rest of the system is remarkably simple and identical across all brands of all ages. There are cables to the three feedback transducers for Stroke, Load and Strain, there is a fourth cable to the servovalve and a fifth one enabling safe operation of the hydraulic powerpack. By merely reconnecting these cables to a new control system, an ‘old system can be made new’.

BISS servo-control technology can also be used to convert legacy hydraulic UTMs and even hydraulic pulsators (manufactured sans electronics) into fully computer controlled test systems. This allows the continued use of systems going back to the 1940’s, but empowered with state-of-the-art quality in control and measurement. When ‘old hands’ in many labs claim better results with older machines, it may just reflect on their comfort level with what they had got used to over many many years.

Over the past 25 years, BISS personnel have upgraded tens of legacy test systems worldwide, of virtually every brand name with new digital controls and the required suite of state-of-the-art application software. **Figure 26** shows a triaxial wheel tester at Accuride Inc in the US, the first complex multichannel test system retrofitted in 2000 with the BISS Imacon controllers, (now, themselves, obsoleted by several generations of new controls!). The retrofit included control integration with a 80-channel strain gauge data acquisition. Accuride end-user deeply appreciated the new capability for fully automated testing with data acquisition that freed up manpower to perform other tasks. At the end of each test, the customized BISS software would put out a spreadsheet of strain gauge readouts characterizing strain distribution across the wheel under different loading actions. And we at BISS learnt firsthand, the importance of user friendly software that could be used by less qualified manpower. **Figure 27** shows a flight simulator supplied to Indian Air Force (by Thompson CSF) for pilot training. The analog control system of this, about 30 years old system, was retrofitted, in year 2010, with BISS 2370 controller with 16 DAC outputs, 32 ADC and 48 DIOs.

Also, worthy of special mention is the recent collaborative effort with the lead test centre of the Russian Railways. The centre continues to use decades old hydraulic 300-ton pulsators to test wagon wheels. These systems consume just 10% of the power of modern servo-hydraulic test systems. But this 'green' advantage is offset by the total lack of control over the mean load being applied that can drift considerably. Decades ago, it was acceptable to have an operator continuously keep track of and adjust mean load. Not anymore, as laboratories prefer power-heavy servohydraulic options as being more consistent even if much more expensive to buy and operate. BISS scientists worked with colleagues at the Russian centre to fully automate the mean load control on their fifty years old test system (**Figure 28**)! The system now delivers excellent test results at a fraction of the cost of any replacement. This was another feather in the cap of the 2370 Series control architecture and technology.

Figure 26 Triaxial wheel tester at Accuride Inc. USA.

Figure 27 6-actuator flight simulator with Indian Air Force.

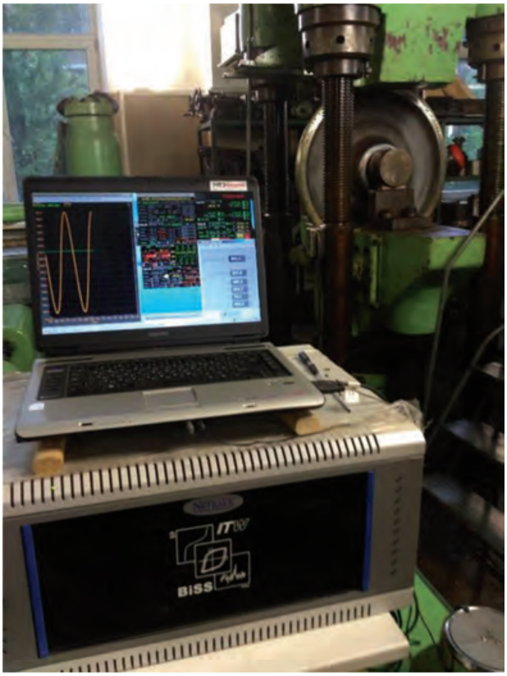
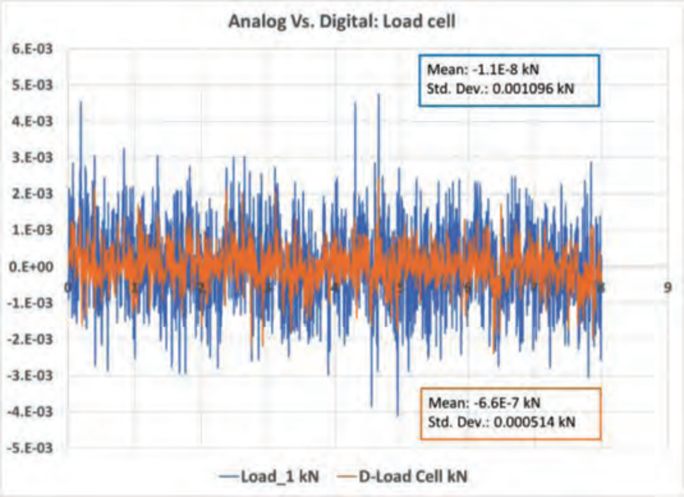


Figure 28 300-ton wheel test system with pulsator at the Federal Research Institute of the Russian Railways.

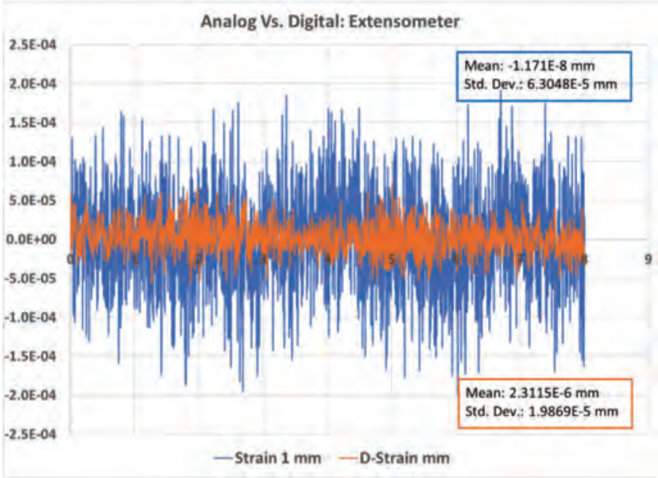
5. Tensile Properties of Materials

Ultimate stress, yield stress, elongation and Young's Modulus are among mechanical properties important to end use, including both quality control as well as design and R&D. Of these, Young's Modulus is most sensitive to quality of measurement because it represents the slope between estimated stress and estimated strain. In metals, modulus is 'constituent dependent' and therefore unlikely to be affected by material processing including heat treatment, etc. modulus has therefore not enjoyed the degree of emphasis on quality in measurement that composites do. In composites testing, the quality of modulus measurement is of utmost importance. modulus of composites is extremely sensitive to a number of parameters including fibre content, layup and curing process, not to mention fibre and resin properties. In a built-up structure, local stresses will vary depending on local stiffness and will therefore be sensitive to modulus. For this reason, fatigue test results for composites are often expressed against strain rather than stress.

Precision of force and displacement measurement together determine the quality of modulus measurement. Analogue measurements carry the natural disadvantage of signal noise as well as potential non-linearity that can adversely affect measurement precision. Further, both force and displacement measurements on conventional test systems rely on analogue transducers and signal conditioners that suffer from cumulative sensitivity to environment related drift in gain as well as offset. A breakthrough in this regard comes in the form of the *world's first fully digital test and measurement system from BISS* with unmatched level of both linearity and resolution in measurement. The new system carries no analogue elements, leading to elimination of noise. Their *unique patented design also renders them drift free*. These together ensure unprecedented resolution and accuracy to define a new paradigm in the domain of measurement.



(a)



(b)

Figure 29 Quality of analog vs. digital measurements: (a) loadcell; (b) extensometer.

A comparison of the quality of fully digital measurement as opposed to analogue electronics can be made from the results shown in **Figure 29** and **Figure 30**. Improved reproducibility of modulus measurement also benefits the testing process through improved means of ensuring specimen alignment.

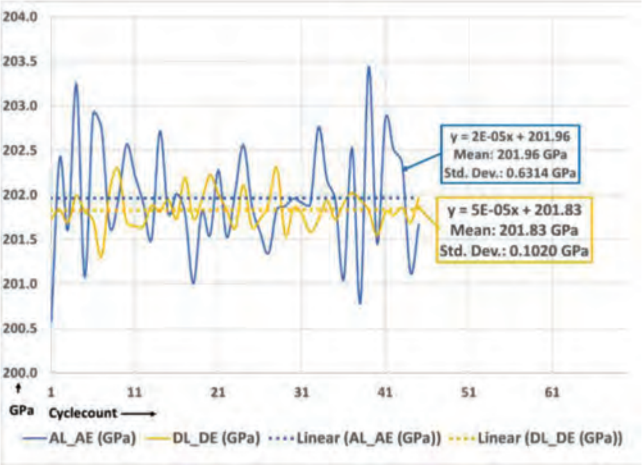


Figure 30 Comparison of quality of fully digital system versus analog system measurements: AL_AE: analog system (analog loadcell and analog extensometer); and DL_DE: digital system (digital loadcell and digital extensometer).

6. Low-Cycle Fatigue Testing

Commercially available software used in industrial fatigue design relies on low-cycle fatigue properties to assess the durability of components. Low-cycle fatigue properties are also of interest in alloy development and characterization studies. The key feature of a low-cycle fatigue test is that testing is performed under *strain control*. Testing under strain control renders the test process immune to the onset of plastic deformation, that under stress control can result in variation of strain amplitude or even specimen failure by uncontrolled extension. Assuming cyclic plastic strain amplitude is the prime driver of the LCF process, the option of plastic strain control rather than just total strain control provides the advantage of ensuring reproducible test results even in the event of cyclic strain softening or hardening.

A number of special requirements need to be met to obtain satisfactory test results from low-cycle fatigue testing. Specimen alignment is an important requirement because any presence of a bending component will accelerate the fatigue process resulting in an invalid test result. Specimen alignment at higher strain levels also protects against premature specimen buckling in compression. Several accessories are available to ensure proper specimen alignment (**Figure 31**). A standard accessory is the load frame alignment kit that can be used to reposition the load cell to ensure co-axiality of specimen mount at the load cell end with that at the servo-actuator end. To register the actual alignment of the load train, a specially instrumented specimen is available that permits the detection of both C-type as well as S-type bending components under tension-compression loading. *BISS 2370 Octa and MS controller models are equipped with additional strain channels specifically to accommodate the instrumented alignment verification specimen in order to simultaneously monitor the output from up to twelve strain gauges sensing strain at the top, middle and bottom sections as required by ISO17025 and Nadcap*. This feature permits periodic alignment verification and correction without the requirement for additional strain logging and data acquisition equipment. Specially designed alignment correction software readily points to the kind of corrections to be made so that the next test can proceed in strict conformance with standard practice. Finally, *BISS low-cycle fatigue grips are of unique design – they are both self-aligning and self-locking*. They eliminate the requirement of spiral washers and contain spherical seats to eliminate bending stresses during gripping. These features together with versatile application software offer unique capabilities in low-cycle fatigue testing. This includes precision total and plastic strain control (**Figure 32**), dual-mode adaptive control to enforce required symmetry in the load cycle and the *unique ability of unloading specimen at zero-stress, zero-strain* (**Figure 33**a) to enable test interruption requiring momentary removal of specimen from the machine. This unique ability ensures the absence of any residual plastic strain at the point of specimen removal (see **Figure 33**b).

Low-cycle fatigue testing may be performed at elevated temperatures (**Figure 34**). This requires a furnace assembly or induction heater. Also, a suitable extensometer is required. A whole range of axial and diametral extensometers were developed over the years at BISS, suitable for a wide range of temperatures, from -190 to +1600C. With resolution, better than a fraction of a micron, they permit quality low-cycle fatigue testing under practically any type of environment. In its Silver Jubilee Year, BISS will introduce *digital extensometers with resolution, hysteresis and linearity in the sub-micron range*.

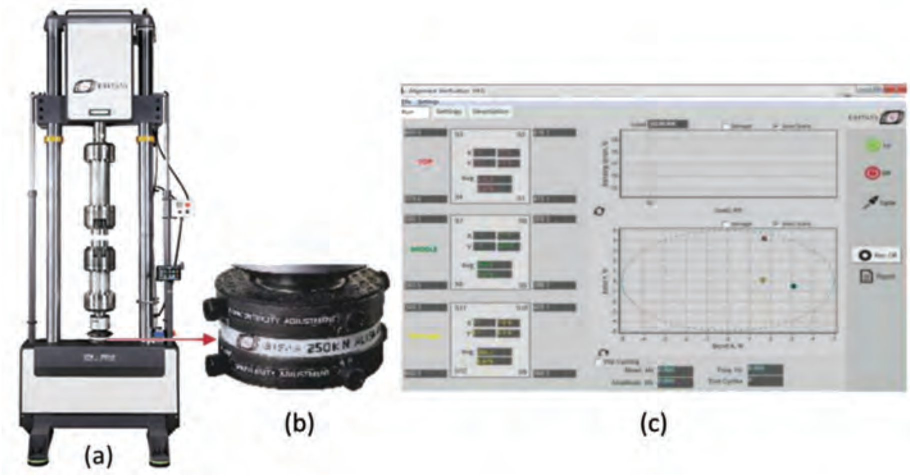
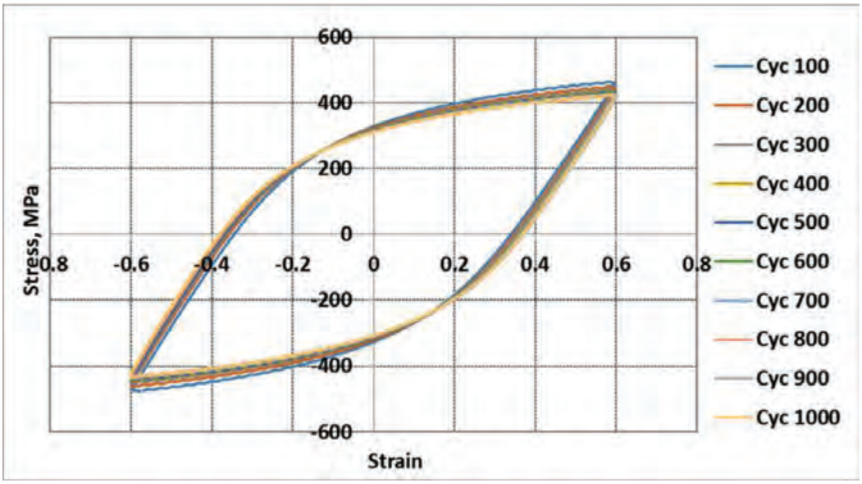
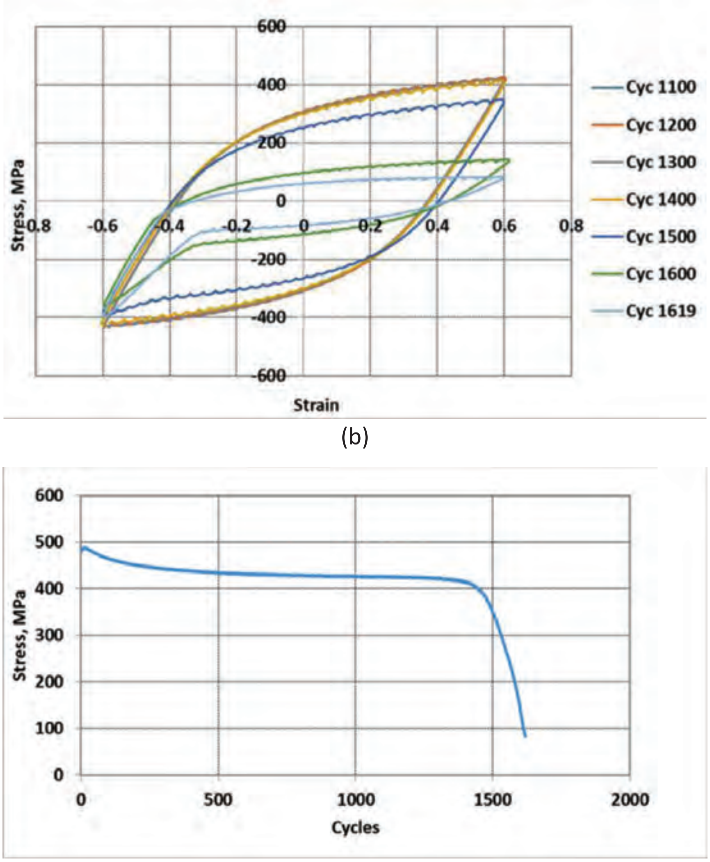


Figure 31 Alignment kit: (a) UTM; (b) Alignment fixture; (c) Alignment verification software.



(a)



(b)

(c)

Figure 32 Total strain controlled LCF test: (a) Stress vs. Strain up to 1000 cycles; (b) Stress vs. Strain up to 1600 cycles; and (c) S-N curve.

Elevated temperature low-cycle fatigue testing is typically performed at lower test frequency. For such testing, extendable to creep-fatigue as well as thermo-mechanical fatigue, an alternative solution is available from BISS by way of backlash-free electro-mechanical servo-actuators. The new systems offer stroke resolution of the order of 30 nanometers and render unmatched stability in load and strain control.

Unified and standardized systems for low-cycle fatigue testing are available from BISS to cater to force requirements from as high as 2500 kN down to 10 kN for miniature test coupons. Of these, systems in the range 10 to 150 kN are available with servo-electric drives suitable for testing at elevated temperature.

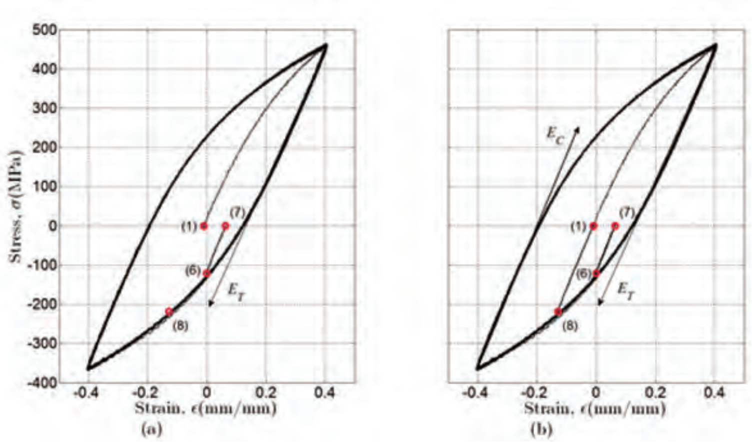


Figure 33 Stress-strain curve for 1-step LCF test:
(a) First step of novel unloading method that follows path (6)-(7);
(b) Second step of novel unloading method that follows path (6)-(8)-(1).

Figure 34 LCF test facility with high temperature furnace, grips and extensometer.

7. Thermo-Mechanical Fatigue Testing

A TMF (thermomechanical fatigue) test is effectively an LCF test with the added feature of temperature cycling. The temperature can be varied in-phase or out-of-phase with respect to strain in order to simulate the actual TMF conditions of machine components that see vast variations in temperature as well as applied loads in the course of a duty cycle. Disks in gas turbines, automotive turbos and nuclear power reactor components are typical examples of safety and fatigue critical parts subject to thermomechanical fatigue.

Several aspects of a TMF test make it extremely complex. The temperature waveform with time needs to be strictly enforced after taking into account potential thermal inertia that can induce its own phase lag with respect to strain variation. Also, temperature across the gauge length needs to be uniform within acceptable margins. There is also the question of inevitable temperature hysteresis between the outer surface of the specimen and the inside imposed by the laws of heat transfer. All these together can impact the reproducibility of test results. But there is a far more challenging aspect that may have restricted the number of global payers offering TMF equipment. This is the *requirement of thermal strain compensation*.

TMF testing requires control of mechanical strain. However, the extensometer measures the sum of mechanical and thermal strain components. It cannot by itself discriminate between the two. This is where the power and performance of the UACE 2020 processor steps in. On BISS controllers, a computed (or virtual) feedback channel is created that computes in real-time, mechanical strain as the difference between measured (total) strain and thermal strain, computed from instantaneous temperature. This calculation is performed over 5000 times a second, providing a steady computed mechanical strain readout that is used for processing, logging and servo-control purposes.

BISS TMF test systems (**Figure 35**) carry a few unique features that account for nuances of TMF testing. Gripping is provided to handle both solid as well as hollow test specimens and to do so with the same degree of alignment as on BISS LCF test systems. Computed mechanical strain accounts for potential thermal hysteresis, eliminating the effect of thermal gradient across specimen thickness. Temperature feedback can be either from a non-contact pyrometer or from thermocouples welded onto the specimen, of which as many as three can be monitored to ensure temperature uniformity (**Figure 36**). BISS TMF systems offer the choice of induction or infrared heating drives. To avoid the potential problem of unintended temperature waveform lag, the 2020 based controller engine directly controls power to the heating device, thereby allowing temperature servo control tuning to proceed in much the same manner as for Stroke, Load or Strain. To the user, the system is essentially a dual-channel (strain and temperature) highly synchronized test system. However, in implementation, it may turn out to be a three-channel system. This is because independent servo-controls may be required for heating and cooling to achieve higher rates of temperature variation. On BISS systems, cooling is servo-controlled using compressed air fed through a servo-valve. **Figure 37** and **Figure 38**a show test results from isothermal cycling and out of phase TMF cycling.

It should not come as a surprise that BISS is one of the select few test equipment suppliers worldwide, offeringthermo-mechanical fatigue (TMF) test systems.

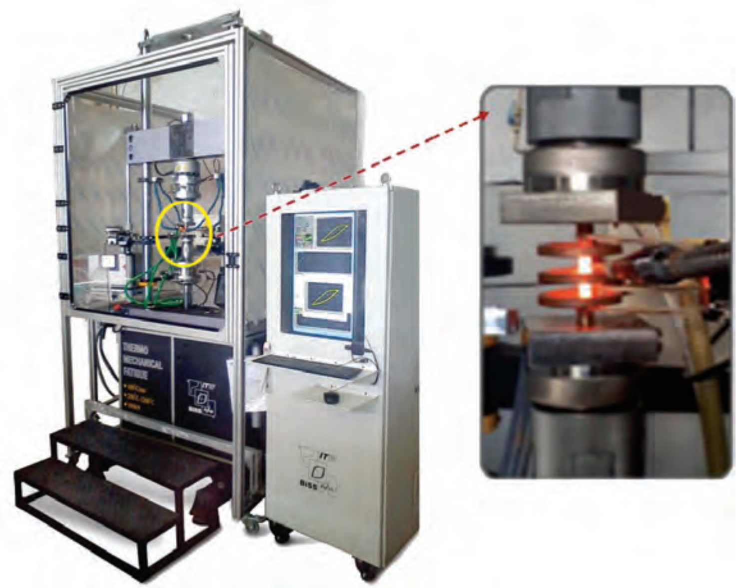


Figure 35 TMF Test System.

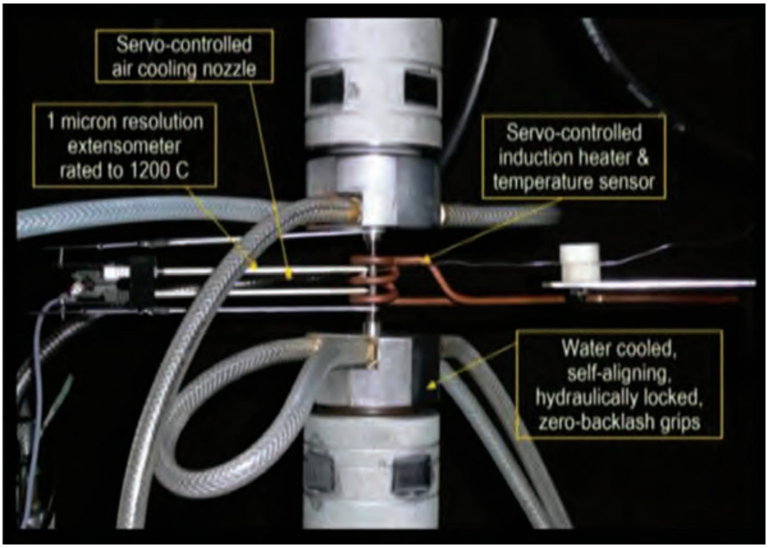
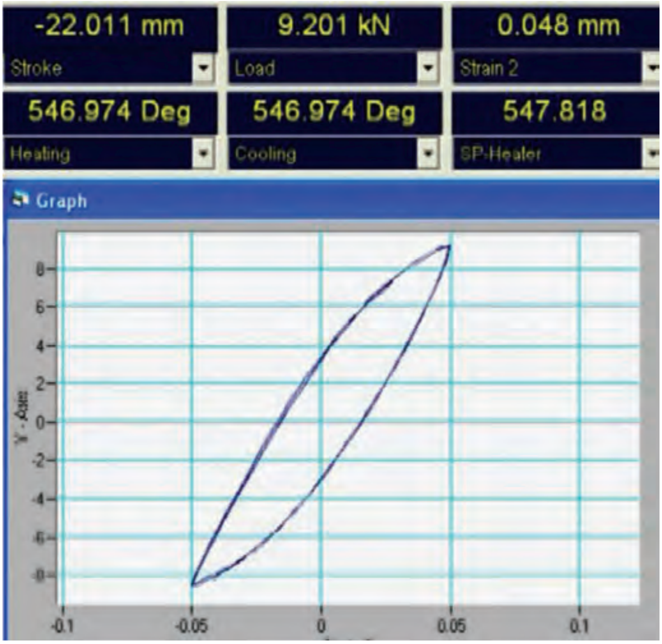


Figure 36 TMF Test Setup.



-22.011 mm
Stroke

9.201 kN
Load

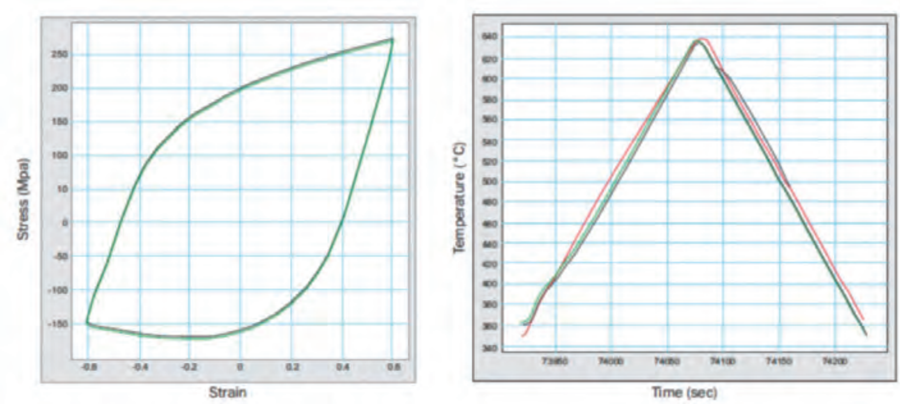
0.048 mm
Strain 2

546.974 Deg
Heating

546.974 Deg
Cooling

547.818
SP-Heater

Figure 37 Strain controlled isothermal cycling: load vs. strain.



(a) (b)

Figure 38 Results of simultaneous thermal and mechanical cycling: (a) stress vs. strain for out of phase TMF cycling; (b) comparison of temperatures measured from three thermocouples (at top, middle and bottom) mounted on the specimen.

8. Creep-Fatigue Test System

Creep-fatigue testing is low-cycle fatigue testing with hold-time at maximum or minimum load, or indeed, at a given intermediate load. Hold time allows creep effects to manifest in adding to the damage caused by strain cycling. Hold times can vary from tens of seconds to several minutes. During this period, as strain is maintained constant and stress invariably high at the turning points, stress relaxation will follow and appear as a vertical segment on the stress-strain hysteresis loop. An important requirement of this type of test is therefore the ability to hold strain strictly and without noticeable variation that may distort the creep phenomenon. The rate of stress relaxation will diminish with reducing stress. The transient function of measured stress versus time during hold presents both scientific as well as practical interest. As the function is one of exponential decay, knowing the stress at which creep is negligible can be important in planning how to truncate hold time to accelerate testing and also to quickly determine design allowables for a new material.

Figure 39 Servo-electric test system with three-zone furnace for creep fatigue testing.

Creep-fatigue testing demands high levels of long term stability in controlled temperature as well as strain. It also demands the ability to accurately track small, time-dependent variations in stress over extended periods of time that are inevitably associated with the creep phenomenon. A range of digitally controlled servo-electric test systems (**Figure 39**) with single and three-zone furnaces were developed at

BISS to meet the requirements of creep-fatigue testing. Unique features of these systems include 0.03µm resolution in stroke control, 0.2µm resolution in axial strain measurement and temperature stability approaching +/-1 degree through outer and inner loop servo control integrated with application software. **Figure 40** shows the test results obtained from a creep fatigue test. BISS test systems are also equipped with uninterrupted power supplies to prevent power brown outs and black outs from disrupting the test. In water cooled systems, safety interlocks are incorporated to protect the test from unforeseen failure of cooling.

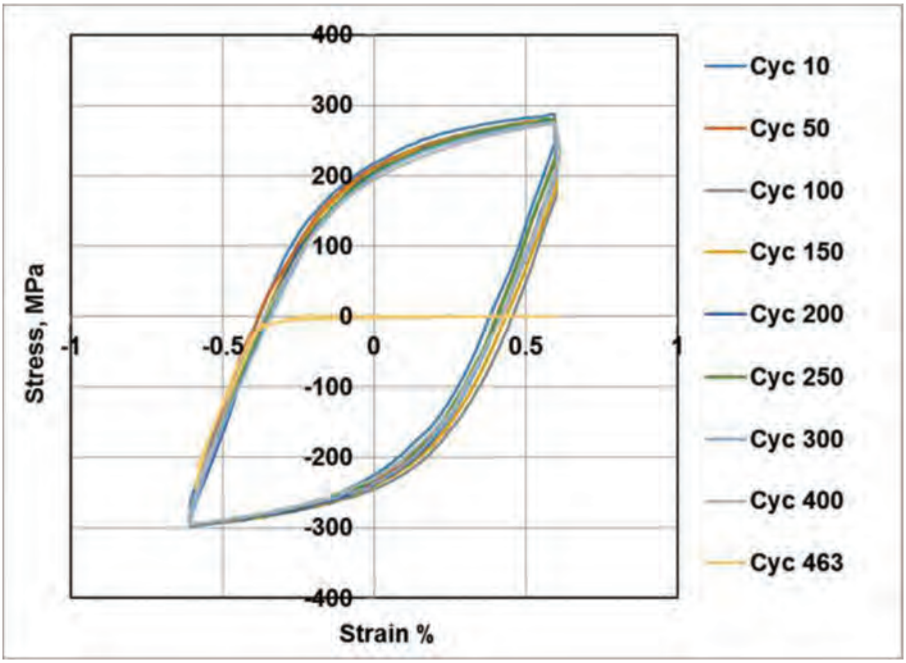


Figure 40 Total strain controlled creep fatigue test results

9. Corrosion Low-Cycle Fatigue Testing

Maritime structures including off-shore rigs, wind turbine towers, ships and submarines need to serve out extended periods of service in extremely hostile environmental conditions including wave action, salt water and salt-heavy, humid air. Conventional low-cycle fatigue (LCF) data are therefore unsuitable for use in designing and assessing durability of such structures, typically made of corrosion-resistant weldable structural steels. S-N curves for these applications demand LCF testing in corrosive environment, representative of actual usage.

LCF testing in a corrosive environment poses a few technical challenges. The gage area needs to be completely soaked in the corrosive medium with provision for circulation to maintain designated corrosive action. Axial and diametral strains need to be measured on the submerged gage area. In close collaboration with leading global players in material development for marine applications and competent scientists from user agencies, all these problems were addressed by BISS R&D. *Unique solutions were developed to track both axial as well as diametral strain to better than 0.3 µm resolution with extensometer arms submerged in salt water.* This permitted obtaining test results of the same quality as in conventional LCF testing. The resultant solution has been proven in sustained contract testing to meet the stringent material qualification requirements for a marine structural steel.

Hour glass specimens are required in the case of welded joints, where the neck of the specimen localizes weld region, LCF response at which the test is targeted. In this case, axial strain is estimated in real-time as a computed variable that can be used as controlfeedback for total or plastic strain range controlled LCF testing.

Corrosion LCF tests are terminated at the onset of crack propagation that is detected from unloading compliance. In the case of hourglass specimens, diametral strain output cannot be assumed to represent gauge area compliance response considering that crack formation is unlikely to reflect on transverse strain compliance. Therefore, in testing hourglass specimens, an additional large gauge length axial extensometer is used for independent tracking of specimen compliance for purpose of detection of crack formation.

At the conclusion of the test, the specimen is heat tinted, then, fractured in liquid nitrogen to reveal the exact size, shape and morphology of the cracked area. In the case of LCF tests on weldments, additional metallography is required to confirm that the failure indeed took place in the weld region or its interface with base metal.

Based on the extensive experience with corrosion LCF testing, BISS offers all the required hardware and software required for corrosion LCF testing, including dedicated application software package, grips, corrosion resistant extensometers with capability for simultaneous independent measurement of net section transverse strain and gross axial strain for detection of crack formation, baths and pumps required for corrosion LCF testing, protection against corrosion damage to test system, etc. **Figure 41** shows servo electric system developed for corrosion induced low cycle fatigue testing.

Figure 41 Corrosion induced LCF test system

10. Fatigue Crack Growth Test System

Fatigue crack growth properties of materials are a vital input to industrial software used to determine residual fatigue life and life between inspections. They are also vital inputs in alloy development as well as design trade-off studies for material selection. Fatigue crack growth testing is performed to characterise the relationship between crack growth rate and stress intensity factor (**Figure 42**), a Fracture Mechanics parameter that describes crack-tip stress field. This demands the ability to measure crack size during the test and also the ability to modify the magnitude of loading without interrupting the test and to do so in a smooth manner without inducing overloads that can distort fatigue crack growth kinetics.

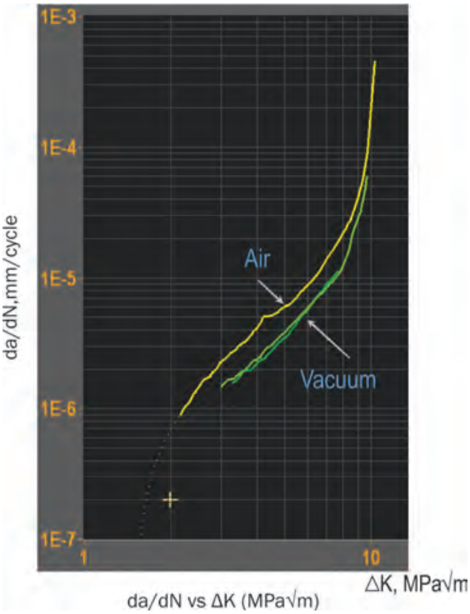
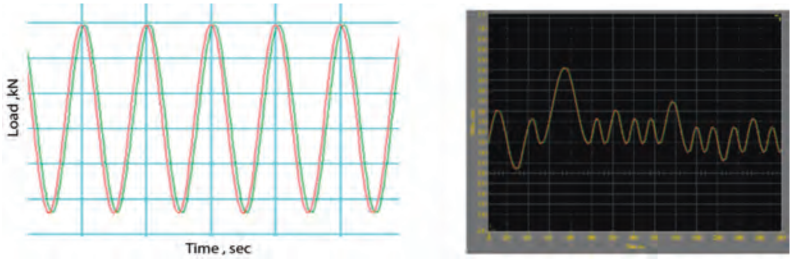


Figure 42 Crack growth rate vs. stress intensity factor.

BISS experience with fatigue crack growth test systems is built around *pioneering expertise developed at the National Aerospace Laboratories in the early 1980's*. This included the capability for *variable-amplitude testing including pseudo-random spectrum loading with iterative correction to achieve precise reproduction of any load spectrum, K-control along with on-line Rainflow analysis to eliminate non-damaging smaller load cycles 'on the fly' in order to accelerate the test process without compromising on the quality of the test, etc* **(Figure 43)**. A review of these appears in ASTM Special Technical Publication 1006. All these features are standard in BISS application software, a unique feature not found on conventional test equipment.



(a) (b)

Figure 43 Fatigue crack growth test waveform: (a) constant amplitude stress control; (b) variable amplitude fatigue loading

BISS test systems provide the choice of crack size measurement through unloading compliance as well as DC Potential Drop (DCPD). Over the past twenty-five years, a number of Crack Opening Displacement (COD) gauges have been developed at BISS. BISS COD gauges are now available to suit practically any specimen geometry (**Figure 44**).

(a) (b)

Figure 44 BISS COD gauges:(a) COD gauge on C(T) specimen; (b) COD gauge on three-point bend specimen.

A unique feature of BISS DCPD units is the implementation of nanovolt-level resolution in DCPD measurement (**Figure 45**) that permits improved resolution of crack increment sensing. This feature along with the standard features of dual signal measurement from both specimen and reference allow the use of the system without the need for electrical isolation of the load train. For the same reason, the technology is

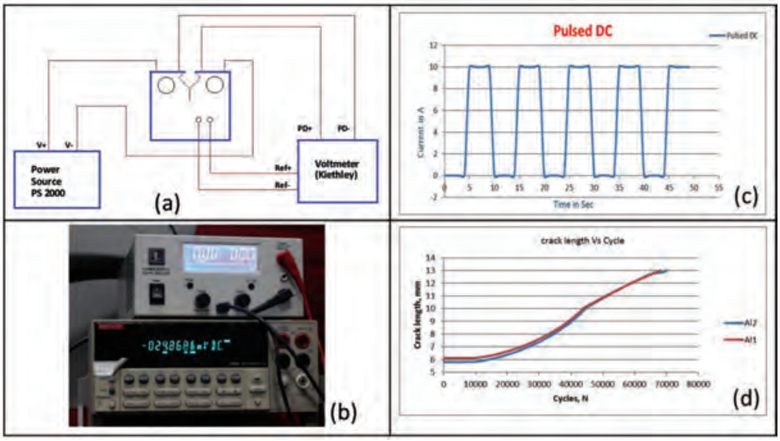


Figure 45 Crack growth measurements using DCPD unit: (a) circuit diagram of DCPD unit; (b) DCPD unit with nanovoltmeter; (c) Pulsed DC input signal; (d)comparison of DCPD and compliance based measurements.

suitable for tests under both constant and variable temperature because measurements are immune to the effect of temperature on electrical resistance.

Both compliance and DCPD based measurement schemes are provided for by prevailing standard practices such as ASTM E647.

More than ten years ago, BISS scientists developed a *unique technique to estimate crack size with reasonable accuracy from force and actuator displacement.* This development was requested by an overseas nuclear research institute that required a fracture mechanics test system to be installed in a 'hot cell', a radiation isolated chamber to test irradiated specimens for fracture toughness. As operator safety is involved, the requirement was the ability to avoid the need to mount a COD gauge onto the specimen to enable specimen pre-cracking before fracture testing. To meet this challenge, BISS R&D adapted a 0.1µm resolution linear encoder to provide actuator stroke feedback. This implies ppm resolution over 100 mm stroke, something unheard of in the testing industry! On the basis of this leap in technology, a procedure was developed to relate specimen COD compliance to load train compliance estimated from force and stroke readouts. The new stroke readout technology was then extended to all systems. It should not come as a surprise that standard BISS materials test systems offer ppm-level resolution on Stroke readout.

Customers have adapted the new technology to other fracture mechanics application. It is known for example that compliance measurements at elevated temperature cannot be performed due to frequency restrictions of high temperature COD gauges to a few Hz. By using the 'remote' compliance measurement (**Figure 46**) developed at BISS, crack growth can be detected without the need for any instrumentation of the specimen itself. This feature is used by scientists in the Defence Metallurgical Research Laboratory in routine elevated temperature testing at higher test frequency.

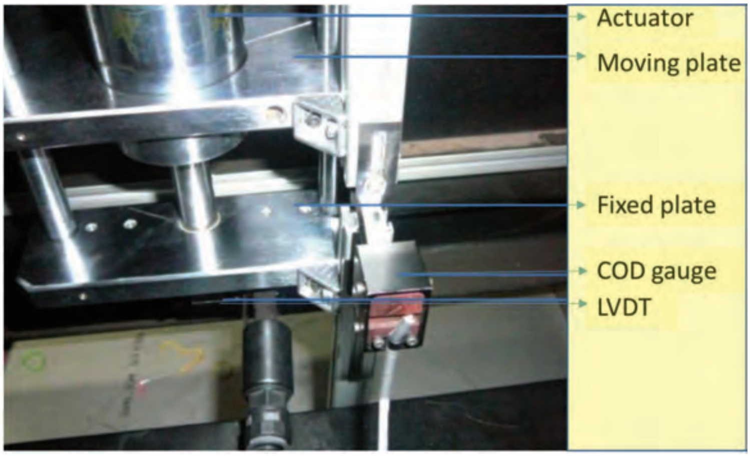


Figure 46 Compliance measurement through a remote COD.

K_{1scc} testing and corrosion crack growth rate testing are somewhat similar to creep crack growth testing. But they are made more complex by the requirement of submerging the specimen in corrosive media and associated problems with gripping, loading and instrumentation. Three-point bend (SE(B)) and compact tension (C(T)) specimens are often used in corrosion crack growth testing.

Servo-electric test systems are best suited for corrosion crack growth testing, given the requirement of slow and steady loading and unloading and also the need for extremely stable, glitch free load over sustained periods lasting several hours, even days. For SE(B) specimens, the actuator is mounted on the top crosshead, along with the load cell. The bottom crosshead needs to be protected against corrosion, along with the bottom reaction fixture with loading pin, that are located within the bath with circulating corrosive medium. The specimen itself is mounted in inverted position, with the crack mouth facing up. In this manner, the specimen can be submerged to the extent required to cover the crack tip, yet, the crack mouth can remain unexposed so that conventional crack opening displacement (COD) gauge can be used to track crack extension. A conventional 3-pt bend fixture connected to the actuator is used to load the specimen. To submerge C(T) specimens in corrosive medium without exposing the loading pins and COD gauge to corrosion, the load frame needs to be placed in the horizontal position.

The corrosion medium needs to be circulated continuously to maintain concentration. Also, arrangements need to be in place to maintain designated level of potential. If required, thermostatic conditions may need to be enforced.

Corrosion crack growth testing benefits from a number of other technological features that may not carry much importance in conventional testing. Test duration can extend to several days and even weeks and given the nature of the corrosion process being time dependent, test interruption can invalidate test results. Therefore, both the hardware and software associated with corrosion crack growth testing need to be validated for extended duration crash-free operation before regular testing can commence. Uninterruptible power supply is an essential element of required hardware. Servo-electric drives can be engineered with a ‘brake assembly’ to lock actuator position in the unlikely event of momentary power failure.

A technologically challenging requirement in corrosion crack growth testing is related to the resolution and reproducibility of crack size measurements from unloading compliance. Any improvement in these not only improves the quality of test results, but also leads to proportionate reduction in the duration of testing.

The BISS range of corrosion crack growth test systems (**Figure 47**) incorporate all the special technological features described above.*A major advancement in this direction was the implementation of precision force and COD measurements that permit reproducibility of crack size measurement on a 50 mm wide C(T) specimen to within 8 µm.* With such reproducibility, reasonable measurements of crack growth rate can be made from increments as low as 0.05 to 0.1 mm, that allows shorter duration of testing even from growth rates as low 10^{-6} mm/s (**Figure 48**).

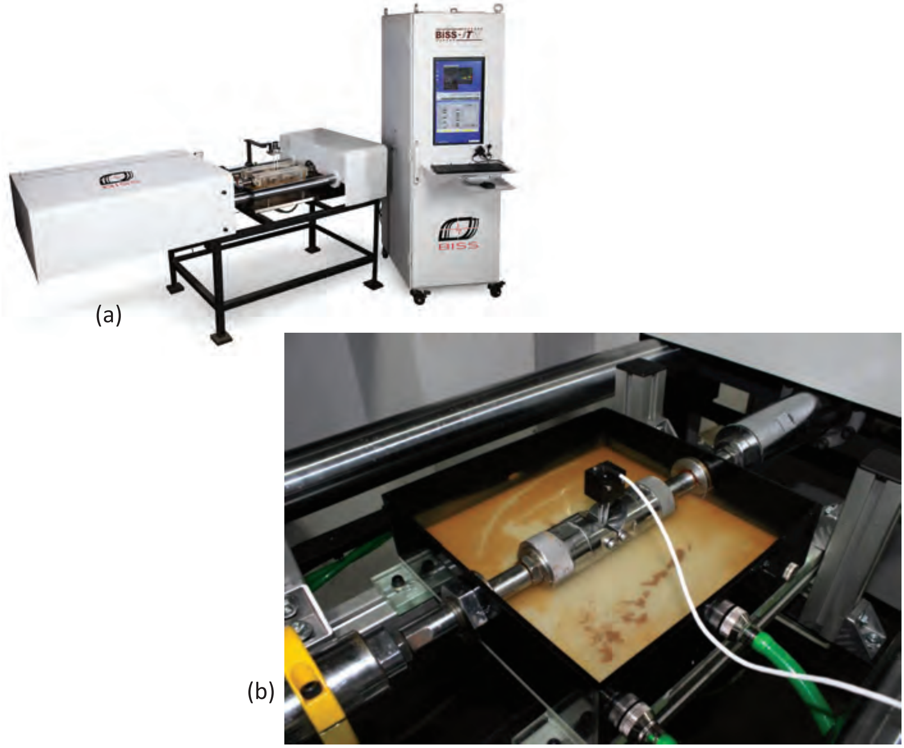


Figure 47 Crack growth testing under corrosive environment: (a) overview complete test setup; (b) close-up of test setup.

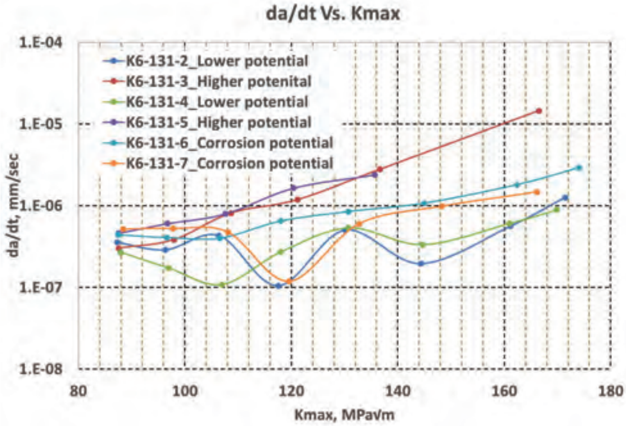


Figure 48 Crack growth rate vs. threshold stress intensity factor under various potential.

Industrial application of fracture mechanics and fatigue crack growth is paying more and more attention to near-threshold crack growth behavior. Such behavior reflects fatigue response at stress levels close to the fatigue limit. For industry, it is a question affecting structural safety in the long term and also the period between inspections. For academia, it is a question of how to develop fatigue resistant microstructures, a question that determines development of advanced materials.

As shown by results published in a recent ASTM Special Technical Publication (ASTM STP 1546), threshold crack growth response can be extremely sensitive to load history. This sensitivity is traceable to the effect of near-tip residual stress on threshold stress intensity, the condition at which the crack can be deemed to grow (**Figure 49**). Establishing this relationship allows more reliable estimates of life between inspections for safety critical applications such as aircraft structures. The test procedure to determine this relationship was developed at BISS R&D.

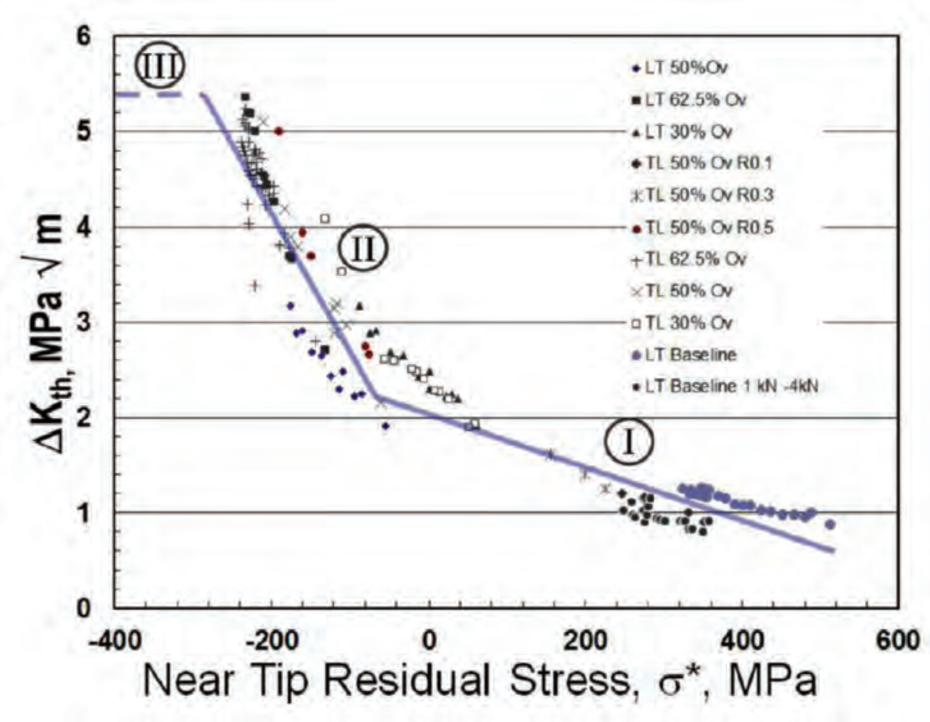


Figure 49 Threshold crack growth response sensitivity to load history: shows effect of near-tip residual stress on threshold stress intensity.

Each of the points in the graph required a few million cycles of testing. Obviously, such testing can take much time. One would like to increase the test frequency in near-threshold fatigue crack growth testing. However, one cannot at the same time go to very high frequencies, say, beyond 1 kHz because this will allow less time for atmospheric effects to manifest via near-tip residual stress, the key parameter affecting near threshold fatigue response. Laboratory testing is typically performed between 5 and 25 Hz. Servo-hydraulics, particularly with the use of voice coil driven spools can achieve frequencies as high as 250 Hz, implying the ability to apply a million load cycles in less than three hours.

The results shown in the above figure were obtained on a BISS test system operating at 150 Hz. Testing was interrupted after every few thousand cycles to determine crack increment from compliance. The 2370 Controller firmware includes a real-time adaptive control algorithm to quickly achieve and hold the desired loading magnitude within 0.5% of assigned levels. This feature makes it possible to obtain highly reproducible test results from testing at low load amplitudes and that too, at frequency as high as 150 Hz, a feature illustrated by the quality of data in the figure.

13. Fracture Testing

A variety of standard practices are followed to determine fracture toughness. Fracture toughness characterises the resistance to fracture of a material in the presence of a defect. The simplest of these is the plane strain fracture toughness test to determine K_{1c}. There is also the critical CTOD (crack tip opening displacement) test that is largely used to characterise the fracture toughness of thick plates, piping material, especially, weldments. And there is the R-curve and finally, the J_{1c} test. ASTM E1820 combines all these practices into a single standard.

The J_{1c} test overcomes the problems associated with interpretation of fracture toughness in the presence of ductile crack-tip response. To avoid this complication, plane-strain fracture toughness (K_{1c}) testing stipulates a limit on crack-tip plastic zone size at failure as a proportion of specimen thickness. Thus, for a valid K_{1c} test result, specimen thickness may need to be unacceptably large if the material happens to be ductile. The J_{1c} test procedure overcomes this problem by separating energy associated with crack extension from the energy associated with crack-tip plastic deformation. *The ability to discriminate between the two energies expended during a controlled fracture process introduces new demands to fracture testing.*

Obtaining reproducible J_{1c} test results requires precision estimates of crack increment during testing, Crack increment is estimated from unloading compliance, whose resolution will be determined by the quality of both crack opening displacement (COD) as well as force readouts. Ideal compliance response of the specimen is also important. This requires the specimen gripping fixture to induce minimum rotational and/or rolling friction. Thus, for compact tension specimens, the clevis holes need to carry a flat region designed to allow the pin to roll as the specimen hinges under loading, particularly with ductile materials. Also, for the same reason, the COD gauge must be able to accommodate a much greater range of COD, than a conventional COD. Finally, the specimen knife edges must be able to see unconstrained rotation within the groove of the COD gauge over the entire range of COD. In the process, the quality of COD readout must not suffer, given the need to detect incremental crack growth of the order of 50 µm or less. Again, the demand for the ability to detect even small crack growth increment is dictated by the prescription of a certain minimum number of crack increment points for a valid J_{1c} test. Finally, test engineers like to enjoy the freedom of specifying the manner as well as extent of unloading to determine specimen compliance. This may be in terms of COD or force. However, the test itself may proceed either under Stroke or COD control, including the specification of Stroke or COD increment.

BISS application software includes all the features and options described above and incorporates multi-mode test control to execute a J_{1c} test without the need for operator intervention at each step. The software caters to the suite of tests prescribed by ASTM E1820 for K1c, CTOD, R-Curve and J1c (**Figure 50**). Absolutely all required fixtures and transducers for testing per ASTM E1820 are standard BISS supply. The fracture test technology from BISS is available as a unified solution on standard test systems (**Figure 51**) ranging in rating from as high as 5000 kN to test very large structural steel sections and down to 250 N to test miniature specimens made from a variety of materials some of these are shown in **Figure 52**.

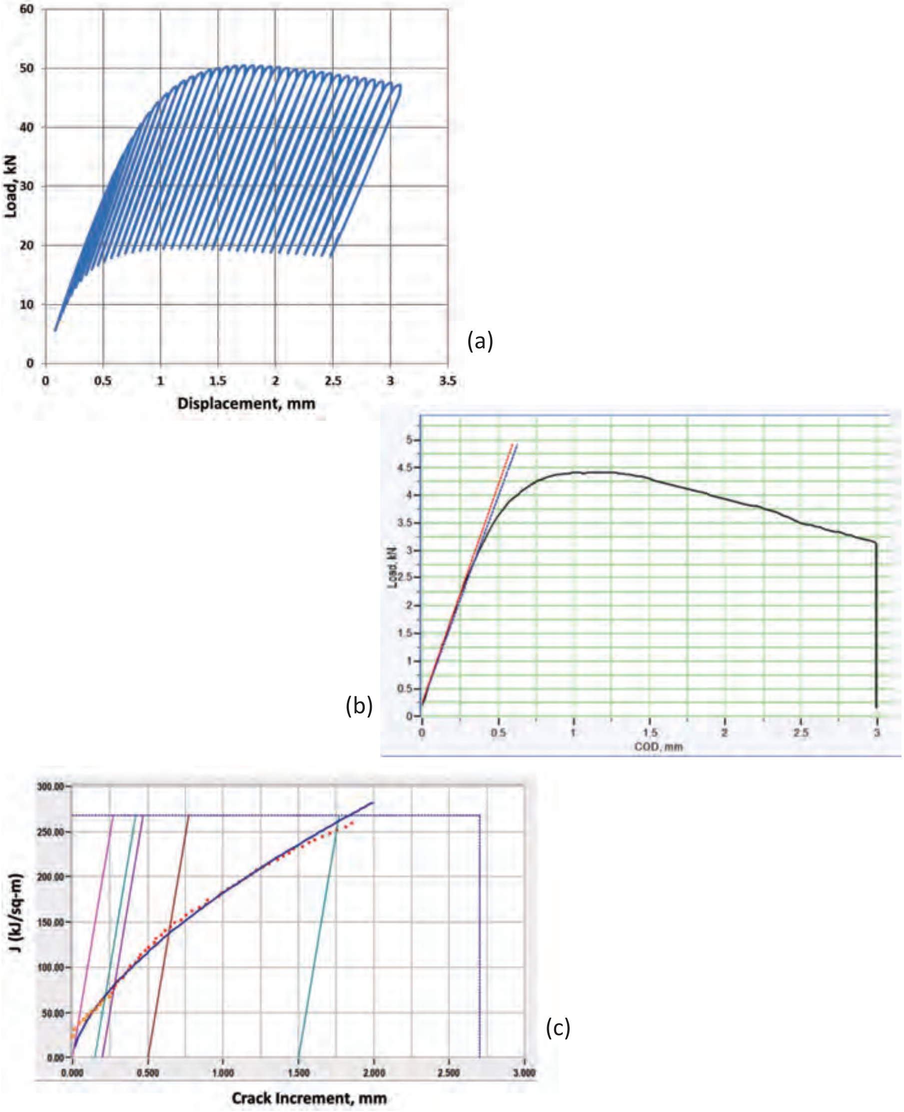


Figure 50 Fracture toughness test results: (a) elastic-plastic loading and unloading curve (Load vs. Displacement); (b) K_{1c} curve (Load vs. Displacement); and (c) J_{1c} curve (Load vs. Displacement);

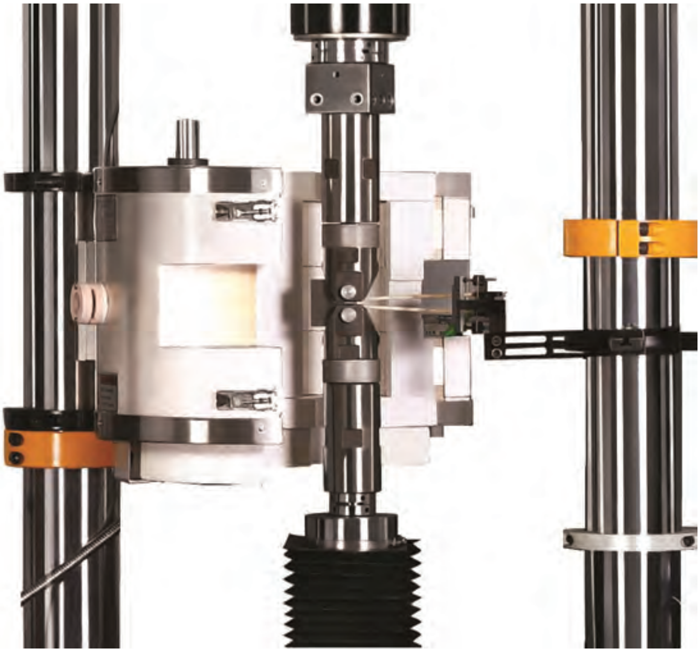


Figure 51 Fracture toughness test setup.

LFS | up to 10 kN Nano | up to 25 kN Median | up to 600 kN Magnum | up to 5000 kN

Figure 52 Versions of BISS material test systems based on force ratings. All these are equipped with fracture test application software and instrumentation

14. Fatigue Test System forFibre Reinforced Composites

Glass fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP) are widely used structural load carrying composites. Their durability is affected by the onset and growth of fatigue damage under cyclic loading, leading ultimately to catastrophic failure. Several features make GFRP and CFRP fatigue testing different from metals. Among these, two are particularly striking. One is the restriction to 5-7 Hz in cycling frequency because of the threat of specimen heating. The other is the very nature of fatigue damage in composites, that is vastly different from metals. Dominant fatigue mechanisms in composites includefiber breakage, fiber pull-out (separation from matrix), matrix delamination and matrix cracking. Thus, unlike a crack in metals, fatigue damage in composites cannot be readily measured in a 'quantifiable' manner, unlike crack size or shape. Unlike one dominant and readily visible and measurable fatigue crack that one associates with metals, fatigue damage in composites can be distributed and sometimes as in CFRP, not even visible.

In the absence of tools to track fatigue damage in composites, a fatigue test on composites has for decades been reduced to just one number – cycles to failure. Composite aerospace structures are in fact designed for 'no growth' conditions even should damage occur, say, by impact. This may dilute the weight advantage of composites as designers reduce stress levels to preclude damage growth. On the otherhand, emerging requirements for fatigue testing of composites include the need to confirm the validity of the test itself. Thus, a test may be deemed invalid if fatigue failure originated from the gripping area. Based on the experience of thousands of fatigue tests on both CFRP and GFRP laminate specimens at BISS Labs, unique technology is now available to handle damage growth tracking in composites. For fatigue testing of GFRP specimens, an imaging system is available that may be programmed to periodically register specimen surface image from both sides. GFRP being translucent is rendered opaque in regions damaged by fatigue. CFRP is opaque and cannot be subject to such imaging. A patented device is now available from BISS that images fatigue damage in CFRP specimens on-line, without interruption of the test (**Figure 53**). The digital imaging is performed using an eddy current

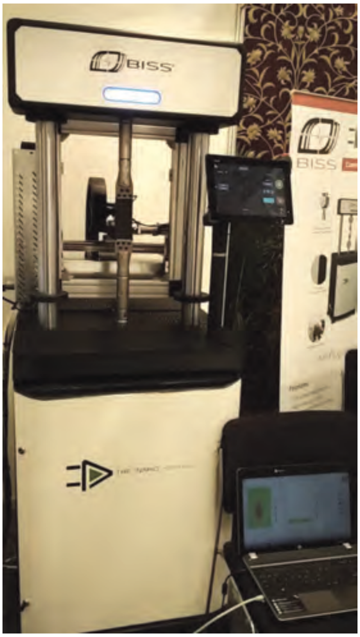


Figure 53 25 Nano static and fatigue test system with 3D online scanner for CFRP specimen.

probe that periodically scans the area of interest on the specimen (**Figure 54**). BISS test systems carry the unique capability of automatically registering the propagation of fatigue damage in both GFRP and CFRP specimens during fatigue cycling. *There is arguably, no other system in the global market that permits fully automated tracking of damage growth in composites in real-time and without interrupting a test.* The accessories required for the purpose are fully integrated with the application software. Data processing software for CFRP damage imaging includes colour rendering of the damage area as well as computation of an equivalent damage size, whose growth can be plotted against cycle count (**Figure 55**).

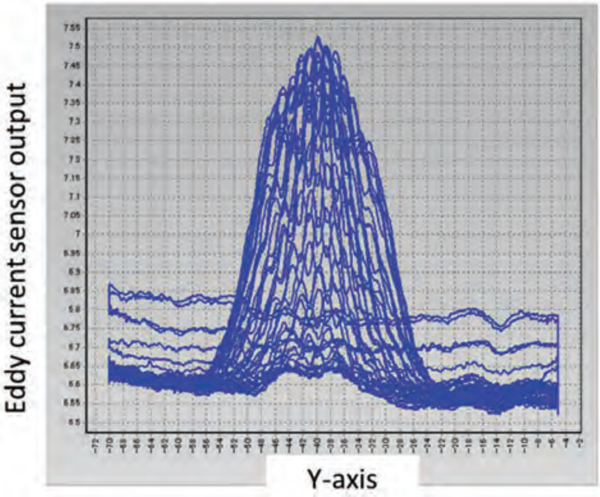
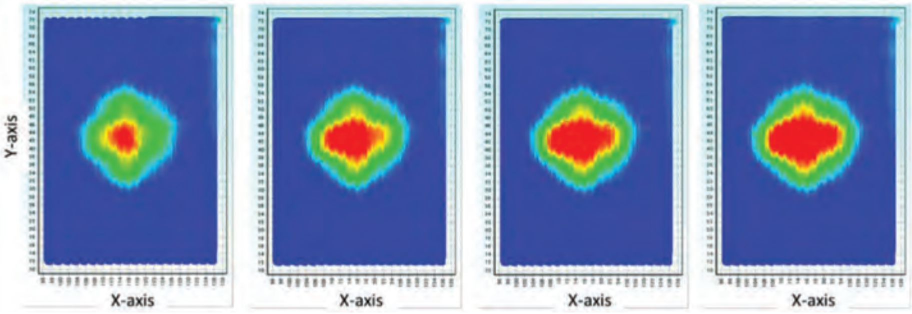


Figure 54 Eddy current sensor output (V) variation across the scanned length of CFRP specimen.



(a) (b) (c) (d)

Figure 55 Rendered damage area of CFRP specimen under various loading conditions: (a) 1.0 kN; (b) 10.0 kN; (c) 20.0 kN; and (d) 30.0 kN.

15. High Strain-Rate Test System

BISS has supplied high strain rate test systems for more than twenty years. The BISS 100 kN high strain rate test system (**Figure 56**) at IGCAR, one of the country's leading nuclear research laboratories was installed in 1994 in collaboration with scientists from the National Aerospace Laboratory. The development effort is described in an ASTM Special Technical Publication (ASTM STP 1303). It continues to deliver quality constant strain rate test data at actuator speeds of up to 3 m/s and test temperatures up to 1000 deg. C. The system was designed for tests with strain rates ranging from $0.01s^{-1}$ to $200s^{-1}$. Typical results are shown in **Figure 57**. As such results (**Figure 58**) are used in evaluating material response under conditions similar to forging and forming, the properties need to be obtained under strictly constant true strain rate. This demands correction of actuator velocity to deliver constant true strain rate even as the specimen gauge length rapidly varies during the test.

Figure 56 100kN High Strain Rate test system at IGCAR.

Another requirement is high speed data acquisition so that sufficient test data are available to characterise material properties even if the test was over in a few milliseconds. The BISS range of controllers are capable of 24-bit data acquisition from multiple channels at rates up to 100 kHz, even though routine cyclic testing may require less than 5 kHz. The BISS high strain rate test system carries another important technological feature that is unique to high strain rate testing. It includes a *'mechanical fuse'* to protect the load cell from damage in the event of an unforeseen overload due to impact. Due to heavy masses in the load train being forced to 'deaccelerate' from 3 m/s to zero within milliseconds, huge inertia related forces are induced that can exceed both actuator and load cell rating. *In over twenty years of operation, no high-strain rate test system from BISS has required load cell replacement due to mechanical failure.*

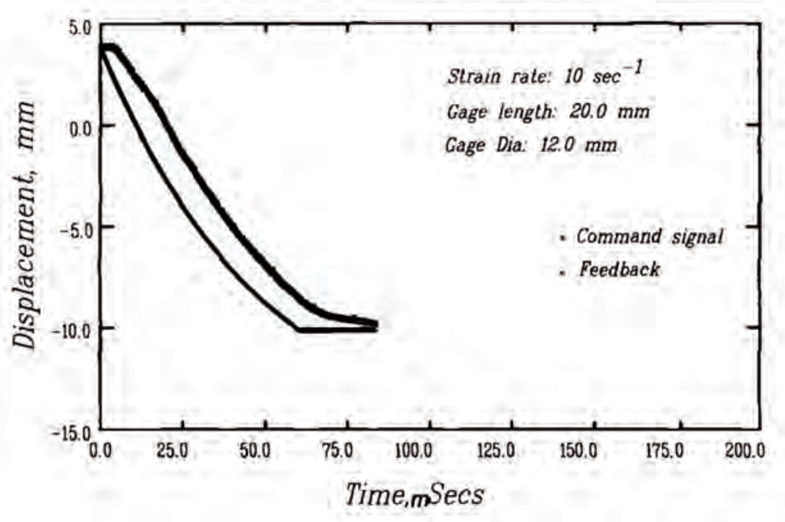


Figure 57 System responses under constant strain displacement rates: (a) 0.1s^{-1}; (b) 1.0s^{-1}(a) 10.0s^{-1}

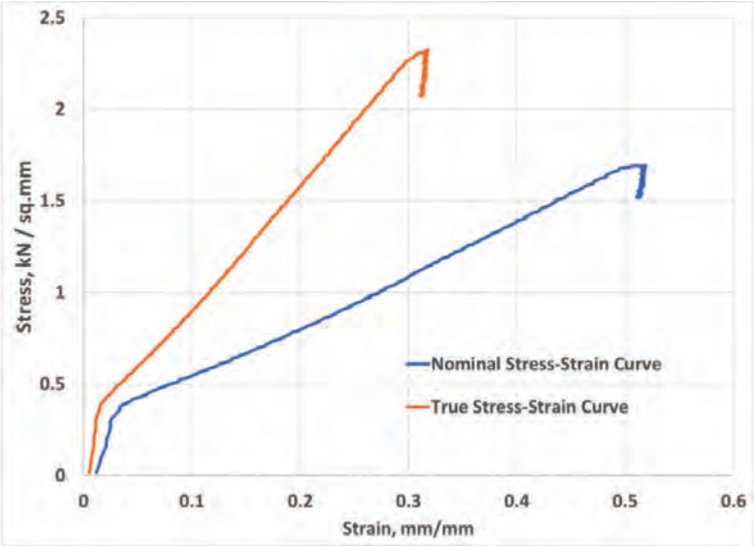


Figure 58 Nominal and True Stress-Strain Curves for strain rate of 1.0/s.

More recently, a high-speed Axial Torsion Test System (ATTS) was developed for IGCAR (See **Figure 59**). The new system carries several unique features. These include self-locking, pre-loaded hydraulic grips, a programmable induction heater and a high speed hydraulic motor capable of several hundred rpm.

Figure 59 Figure 1 High Strain Rate ATTS system at IGCAR

16. High Speed Testing of Plastics and Rubbers

High speed testing of rubbers and plastics provides data required for design of vital automotive parts that contribute to crash safety. These include air bags and dashboard covering. The high strain rate mechanical properties of these materials need to be characterized at different temperatures.

In testing rubbers and plastics for crash safety applications, specimen gage section may be subject to strain rates of up to 100 $s^{-1}$and elongation as high as 800%. A servo hydraulic system with a high frequency data acquisition system is well suited for such an application. Tests at high strain rates typically last for about 3-5 ms. As high strain rate and very high elongation are involved conventional extensometers cannot be deployed. Instead, high speed non-contact techniques such as high speed videography at speeds up to 50,000 fps followed by digital image processing (DIC) is employed. This effort enjoyed the support of scientists from the Siberian Division of the Russian Academy of Sciences. *A challenging problem that needed to be overcome in the process was synchronization of force and actuator displacement readouts with strain readouts from DIC.* Results from these multiple channels are then processed to obtain stress-strain properties of materials such as rubbers that are then used by customers to design air bags and other dashboard components. Such a test setup, specimens and typical test results are shown in the **Figure 60**.

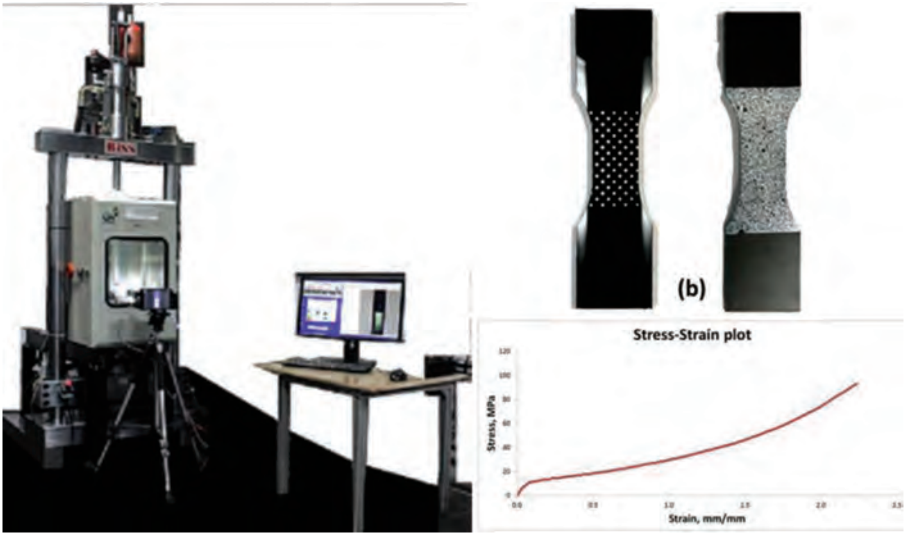


Figure 60 High strain rate test setup for plastic and rubber materials. Tests are performed over a temperature range -60 to +80 deg C. (a) test setup; (b) specimens with reference grid and speckle pattern; (c) stress-strain curve

17. Elastomer Test System

Ride comfort on transportation systems depends largely on the quality of suspension system components. Hundreds of different types of dampers are used on every automobile. Demands on their individual characteristics continue to increase as vehicle weight reduces with the use of lighter materials.If expensive luxury cars are more expensive, they partly owe their enhanced value to the quality and reproducible characteristics of elastomers in place to reduce vibrations and noise. This demands improvement in material and product design supported by testing to validate dynamic properties including dynamic stiffness, elastic stiffness, damping stiffness, energy loss per cycle and phase angle, not to mention, long term durability.

Figure 61 Elastomer test setup with piezoelectric loadcell.

Elastomer properties are determined through controlled excitation on a test system with small amplitudes between 0.01 and 1mm at various frequencies right up toseveral hundred Hz. The critical requirement of such testing is the ability to accurately *and synchronously* measure force and elastomer displacement over such a wide range of frequency. Synchronous measurement is complicated by the different nature of force and displacement transducers with the inherent possibility of incorrectly perceived phase difference between the two that would distort damping property estimates. It is also important to ensure that the load frame is extremely stiff so as not to introduce superposed effects that can distort measured properties. To ensure superior quality of elastomer testing, BISS test systems (**Figure 61**) are equipped with linear digital encoders that deliver noise free synchronized 0.1 µm resolution readouts of displacement and 24-bit resolution force readouts from piezo-electric load cells at data acquisition rates as high as 32 kHz to ensure sufficient incremental readouts of both force and displacement even at displacement ranges as low as 10 µm. Unique dual mode real-time control at controller processor level permits simultaneous control of assigned mean *force* and *displacement* amplitude, that are essential to enforce test conditions often prescribed by demanding customers. Also, given the unmatched quality of high resolution digital displacement measurement, computed variables in the form of velocity and acceleration as its first and second derivative are available in order to correct inertia components if any. **Figure 62** shows the dynamic stiffness vs. frequency for various samples tested on a BISS 25 kN test system.

With its vast experience in elastomer testing, BISS has been called upon to supply a variety of multi-axial elastomer testers (**Figure 63**) at the component level, ranging in capacity from 5 to 500 kN. These systems are used by leading automobile manufacturers to evaluate the performance and durability of critical suspension components under simulated multi-axis road load conditions (**Figure 64**).

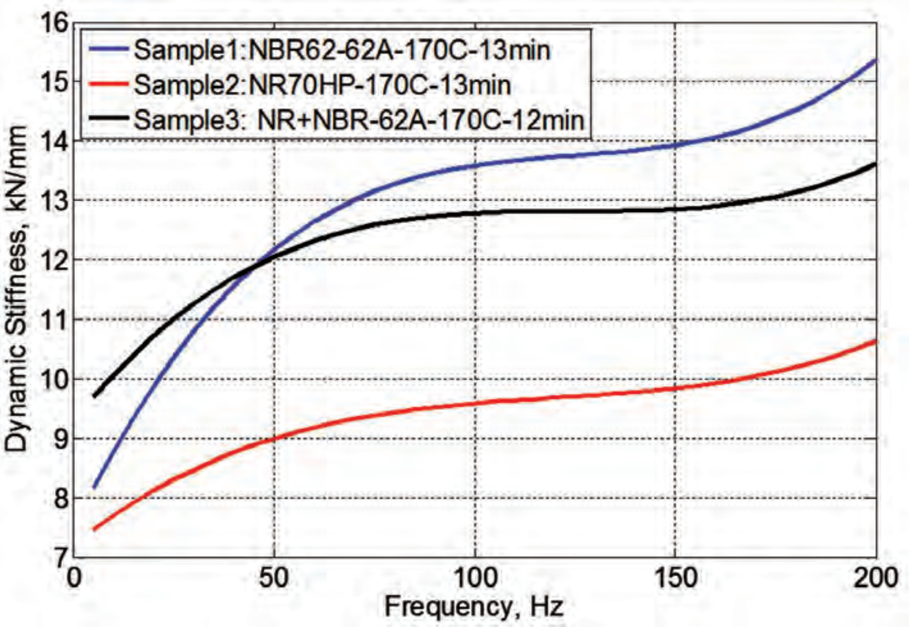


Figure 62 Dynamic stiffness vs. frequency plot for various samples.

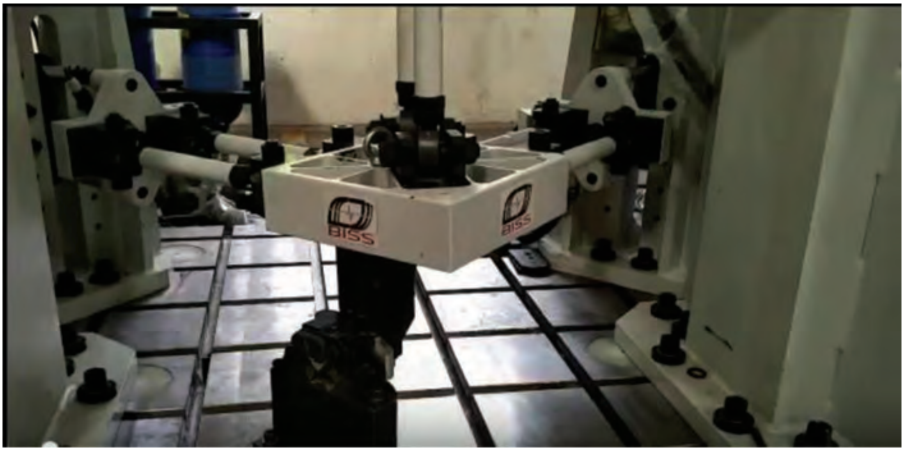


Figure 63 Multiaxial elastomer test system.

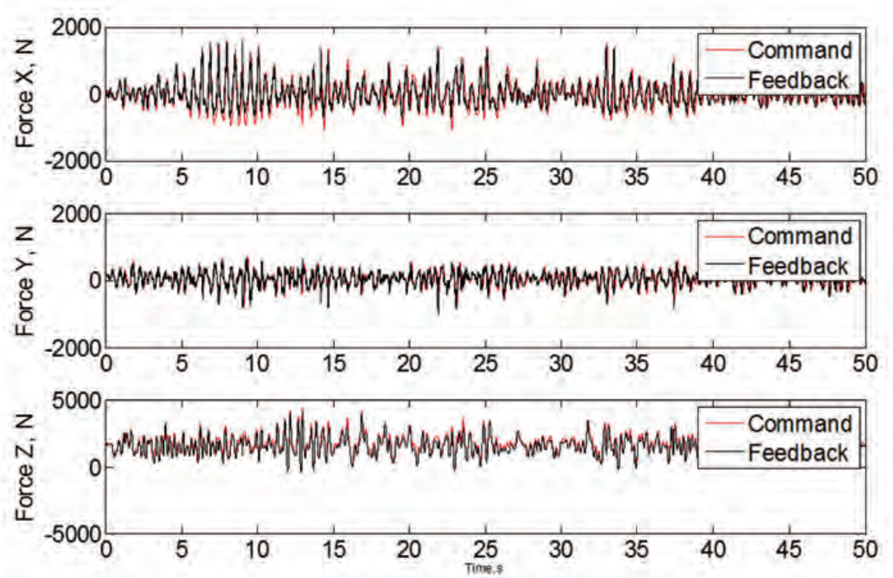


Figure 64 Road loads simulated on a triaxial elastomer test system.

18. Low Force Range of Test Systems

Most universal testing machines (UTMs) have a capacity ranging from 50 to 250 kN. This is because standard practices to determine strength, toughness and durability of metals and high strength composites involve test coupons that will fail under such loads. In contrast, material testing of biomaterials, microelectronic components and polymers may require systems that can apply forces in the mN to10 kN range. Continuous advances in additive manufacturing techniques also benefit from the ability to test miniature test specimens for property characterization as well as quality assurance.

To address these requirements an entire range of low force servo-electric systems were developed at BISS (**Figure 65**). *These are built around high performance servo-electric actuators from Japan with extremely high position resolution of about 30 nm.* BISS Low Force Systems (LFS) are equipped with standard features like Test-by-WiFi and Test-by-Wire. BISS Low force range includes single column and dual column load frames. The latter offer the option to operate in either vertical or horizontal position.

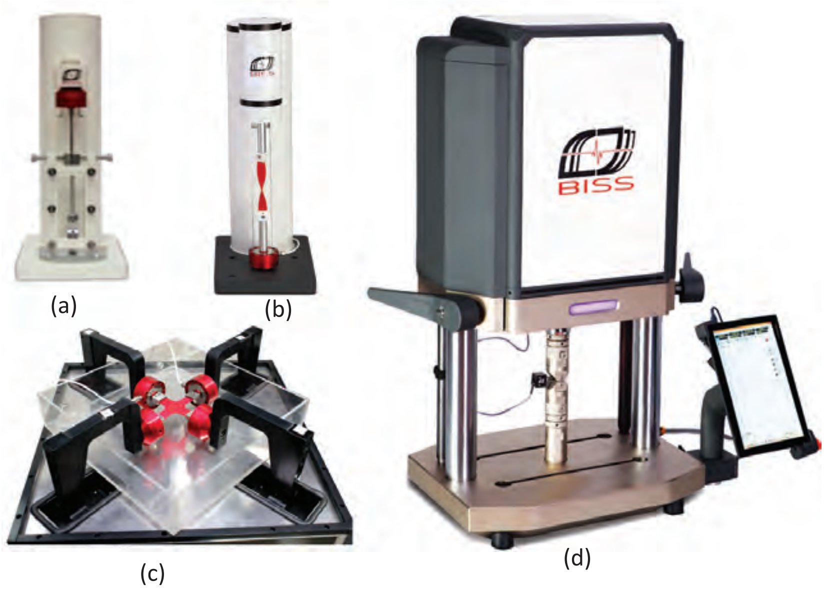


Figure 65 Low force test systems:(a) A perfusion bioreactor in an OsteoGen test system; (b) monocolumn axial-torsion test system (200-500N) ;(c) biaxial test system (500-2000N); (d) dual column uniaxial test system (2-10kN) (this system can operate in both vertical as well as horizontal position).

Single footprint systems such as the dual column 10 kN LFS (**Figure 65**d) are widely used in medical and microelectronic applications, given their versatility and wide array of grips suitable to determine precise test parameters. Introducing temperature as a factor to evaluate material performance is critical and challenging. Saline bath with temperature controlled media is one such requirement where Corrosion Crack growth studies can be pursued with miniature specimens.

Working with biomaterials including tissue culture and regeneration application need systems that can apply low force mechanical stimulation continuously at in vivo conditions (**Figure 66**). The Low force lineup was meant to operate under such conditions including its ability to maintain normal operating temperatures over prolonged periods within an incubator. Sterility with reusable bioreactor chambers and ease of cleaning is another feature of the LFS range.Specially designed grips for testing intraocular lenses are also available (**Figure 67**). The application demands a high degree of precision and high resolution force measurement down to mN.. The load frame is further isolated with a chamber to reduce transient noise generated by the environment.


(a) (d)
(b) (c) (e)

Figure 66 Bioreactor Test Systems: (a) A perfusion bioreactor in an OsteoGen test system; (b) A tension DermiGen bioreactor test system; (c) A tension LigaGen bioreactor test system; (d) A compression CartiGen bioreactor test system; (e) A pressure simulation LumeGen bioreactor test system.

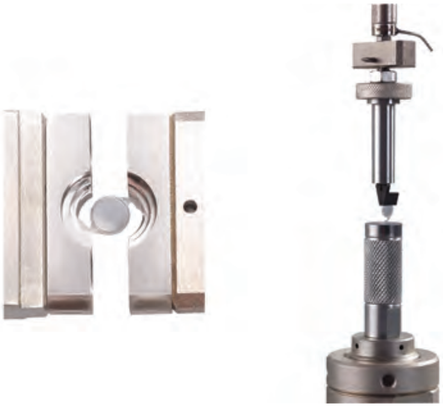


Figure 67 Grips for testing intraocular lenses; (a) tension test; (b)compression test.

19. Miniature Specimen Testing

Prevailing standard practices stipulate certain dimensions of test specimens to determine static, fatigue and fracture properties of materials with the desired degree of reproducibility. There has been a growing demand for the ability to determine such properties from smaller specimens. Researchers in nuclear energy supporting the life-cycle operations of power reactors would like to determine properties of irradiated materials. Keeping radiation hazards in mind, it is desirable to resort to as small a specimen size as possible. Specialists studying the properties of materials used in mechatronics would also prefer to work with miniature specimens and so would specialists involved with additive manufacturing technology. Even a very down to earth requirement of material property characterization along the thickness direction of rolled plates would involve specimens about ten times smaller than conventional standard ones.

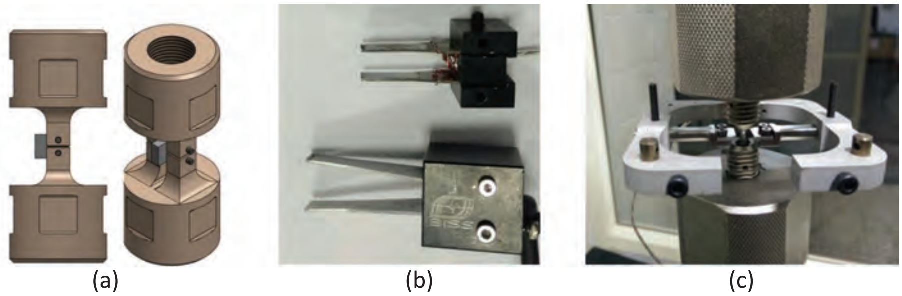
To test specimens ten times smaller (**Figure 68**) than conventional coupons, one would require a test system proportionately smaller in force rating, but with measurement quality several times superior to make up for the demands on relative accuracy of measurement. Servo-hydraulic actuators have virtually no upper limit in force rating. However, as force rating drops below 10 kN, their efficacy is challenged by limitations on available servo-valves. A range of Low Force Systems were developed at BISS to meet the new requirement. These were augmented by the merger into BISS of the entire product range of Instron-TGT (Tissue Growth Technologies), a Minneapolis company specializing in tissue engineering and characterization applications. The new range of test systems starts from as low as 40N using high performance acoustic coil drives tested at up to 300 Hz cycling frequency and goes up to 10 kN dynamic rating using high performance servo-electric drives, with capability of cycling at up to 25 Hz (**Figure 66**).

Grips and transducers (**Figure 69**) were specially designed to enable static and LCF testing of specimens as small as 15 mm in length and fatigue crack growth and fracture testing of specimens less than 20 mm in width. These enable material property characterization in the thickness direction of plates less than 20 mm thick! **Figure 70** and **Figure 71** show tensile and LCF test results on a miniature specimen.

Accuracy of strain measurement is limited by the accuracy not only of displacement measurement, but also of gauge length itself. A major challenge in measuring strain on smaller gauge lengths is the ability to accurately characterize the actual gauge length over which displacement was measured. Much effort at BISS R&D was devoted to the resolution of this problem before finally, acceptable reproducibility could be achieved in material property characterization.

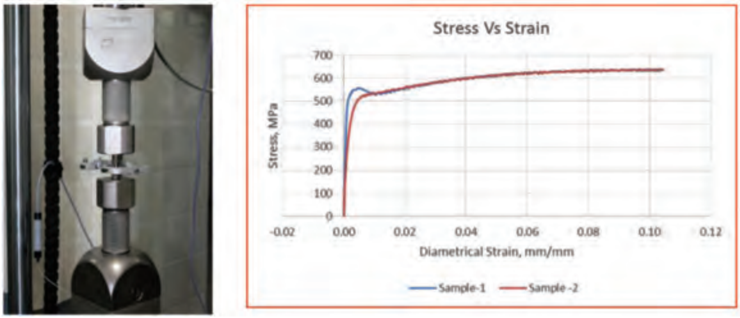
(a) (b)

Figure 68 Miniature specimens tested on BISS low force test systems: (a) tensile / LCF specimen (M5 mm, GL 3mm); and (b) Fracture toughness / Fatigue crack growth (W12 mm, T5 mm).



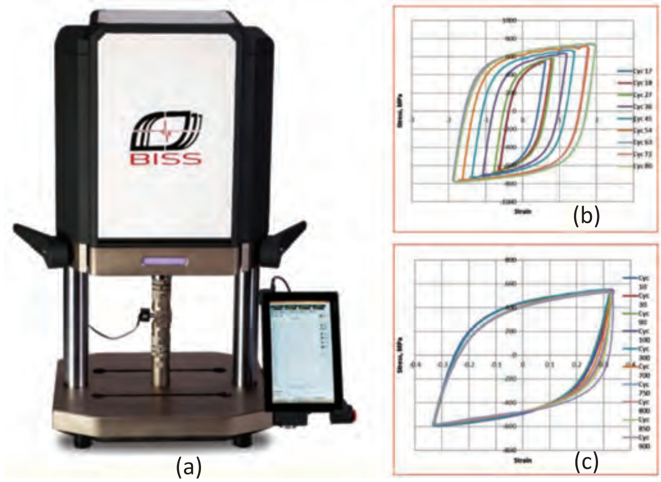
(a) (b) (c)

Figure 69 Miniature specimen fixture: (a) fixture: W12mm, D3mm, T5 mm; (b) COD:GL 3mm, Range ±1.0 mm, resolution 0.3μm; (c) diametrical extensometer: Range ±0.5 mm, resolution 0.02μm.



(a) (b)

Figure 70 Tensile testing on miniature specimen: (a) tensile test setup; (b) stress-strain curve for a miniature specimen obtained from tensile testing.



(a) (b) (c)

Figure 71 LCF test on a miniature specimen: (a) 10 kN LFT Test System; (b) Strain controlled test in increments of 0.1% up to 1.5% strain; (c) Total strain control test at 0.33% till failure (1150 cycles).

20. Axial-Torsion Testing

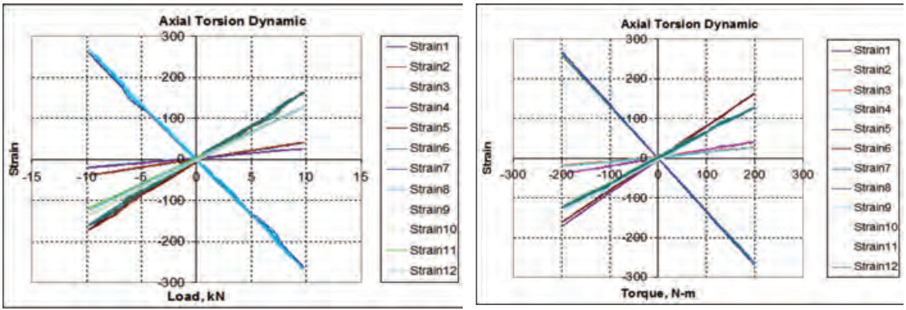
The importance of understanding deformation and fatigue of materials (metals, composites, elastomers etc.) under multiaxial loads, resulting from service conditions, has gained significant recognition by the scientific community towards the development of materials for various engineering structures (piping in nuclear power plant, aircraft, civil, mechanical, vehicles, windmills etc.). Torsional testing reproduces pure shear. Characterization of axial-torsion response serves the development of material constitutive relationships and appropriate failure criteria. Multi-axial testing is also important in evaluating the durability of medical devices such as a knee joint. Guidelines for using axial-torsional tests are available in relevant standards: axial-torsion testing of thin-walled tubular specimens (ASTM E2207), metallic medical bone screws (ASTM F543) and metallic wires (ASTM A938 and ISO 780).

Several challenges confront the development of axial torsion testers: These include (a) cross-talk between the axial and torsional channelsthat affects the quality of both control as well as measurement – axial response affects stiffness in torsion and vice versa, an axial load can distort torsional moment readout and vice versa; (b) specimen alignment to ensure coincidence of axial, torsional and specimen axes; (c) extensometry to handle both axial and torsional displacement on the specimen and (d) specimen fixturing without backlash along either axis.


Figure 72 Axial-torsion test system

BISS, since 2004, has supplied over a dozen axial-torsion test systems (ATTS) worldwide, with rating ranging from 10N to 600kN axial load and 10Nm to 2kNm torsional load with test frequency range up to 50 Hz. These systems are used in various applications from low force testing of biomedical materials/devices to high force testing of civil/mechanical/aerospace materials and structural components. **Figure 72** and **Figure 73** show a typical 100kN BISS ATTS system. **Figure 74** shows stress-strain curves of axial and torsional components under in phase axial-torsional loading. **Figure 75** shows stress-strain curves of axial and torsional components under out of phase axial-torsional loading.


Figure 73 Hydraulics grips and torsional strain measurement systems for ATTS system



(a) (b)

Figure 74 Specimen response under in phase axial and torsional loading: (a) axial strain vs. axial load; (b) torsional strain vs. torsional load.

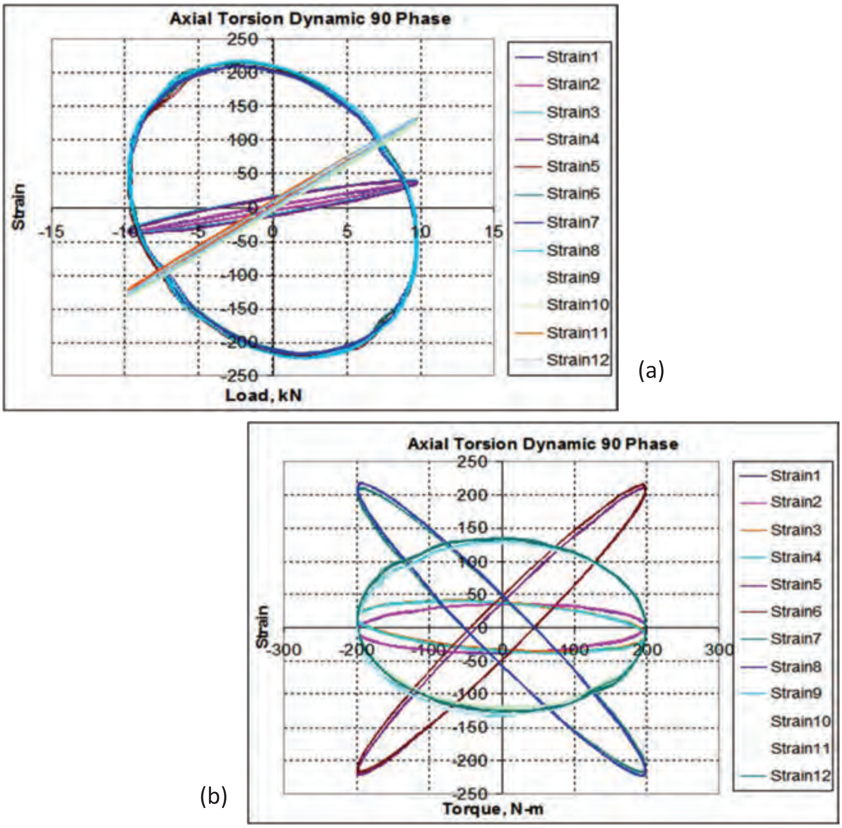


Figure 75 Specimen response under out of phase axial and torsional loading: (a) axial strain vs. axial load; (b) torsional strain vs. torsional load.

21. Planar Biaxial Testing

Most mechanical tests for strength, fracture and durability are performed under uniaxial directions. Indeed, mechanical properties such as modulus, yield stress, ultimate strength and fatigue limit represent uniaxial material behavior. However, most practical situations involve multi-axial loading. For example, any pressure vessel will see biaxial loading from the axial and hoop stress components.

Some ten years ago, scientists from BISS and the Kazan Energy Research Centre in the Russian Federation took up a joint research project to study fatigue crack growth under conditions simulating the skin of a pressurized aircraft fuselage cabin. This involves biaxial loading with cabin pressure inducing constant hoop stress and axial stress component, with superposed axial stress induced by pseudo random flight-by-flight loading from turbulence and maneuvers. To perform such tests, a planar biaxial test system (**Figure 76**) was developed, consisting of four servo-actuators positioned at right angles to each other on a free-standing self-reacting load frame. Planar biaxial test systems differ from axial-torsion systems. They involve the use of cruciform shaped specimens.

While opening a number of new avenues in characterizing material behavior, planar biaxial testing also poses a number of challenges. Considering the variety of problems of interest in biaxial material behavior, the two axes of loading should be amenable to precise independent control in the desired mode (Stroke, Load or local (axial) strain response) and with desired distribution of load and phase lag between the

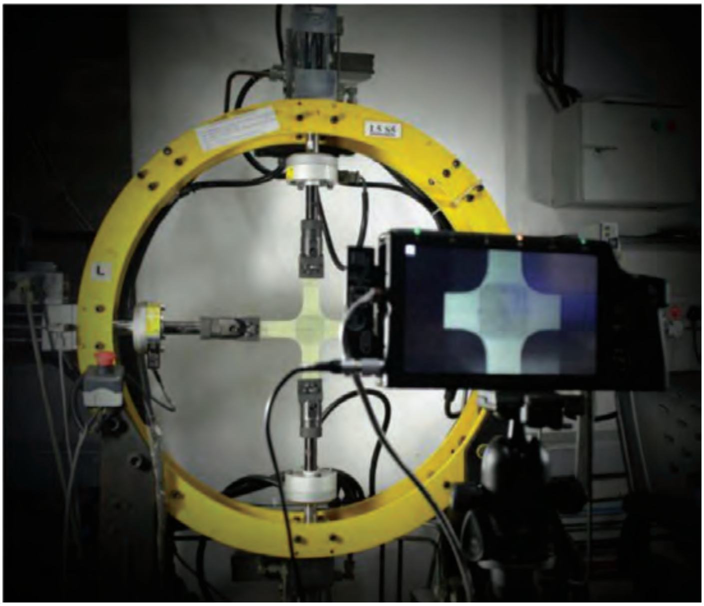


Figure 76 Planar Biaxial Test system developed for Kazan Energy Research Centre.

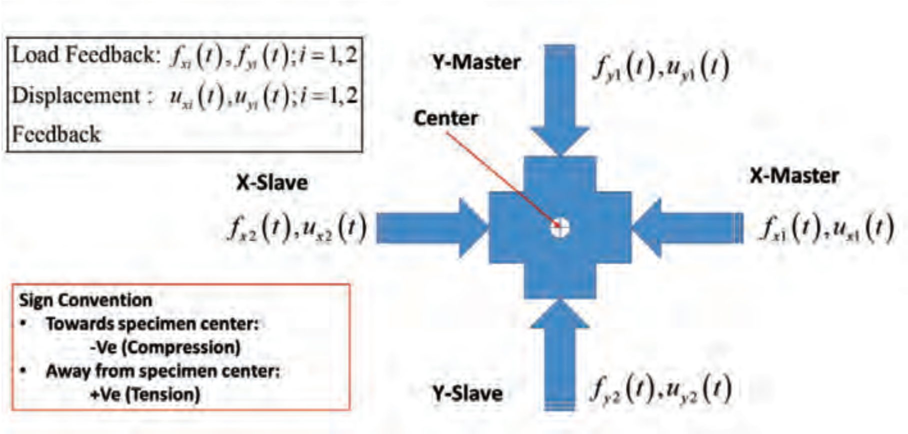
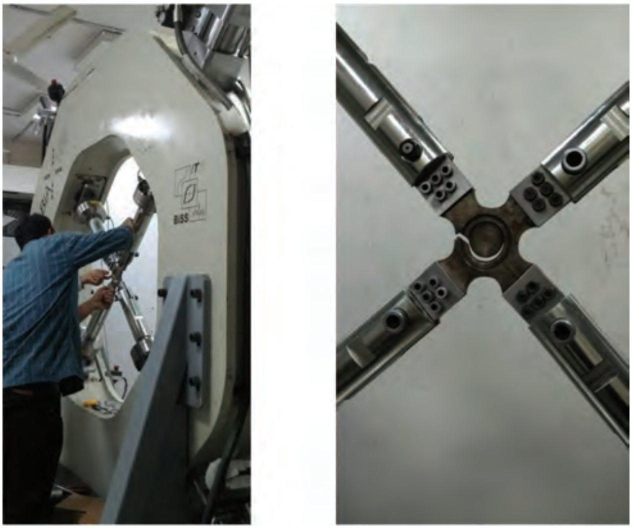


Figure 77 Master-slave operation mode of a planar biaxial test system.

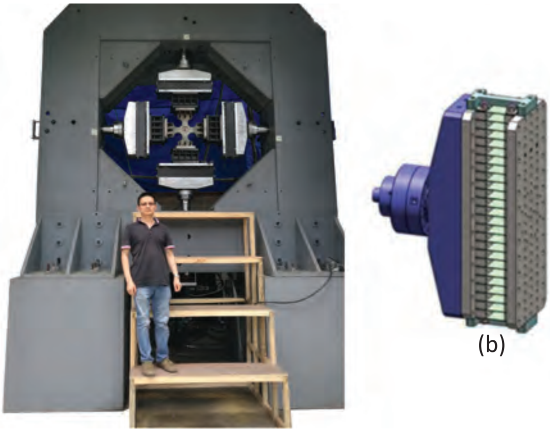
two axes. These requirements are met by most conventional biaxial test systems. There is however an overriding requirement that is particularly challenging. It revolves around the basic need to restrict loading to strictly biaxial, without any shear component whatsoever that may not only distort the desired stress state, but also threaten unintended damage to the specimen outside the gauge area, through shear damage to the tab areas. This requirement must be satisfied not only under quasi-static loading conditions, but also under cyclic loading. The conventional approach to meeting this requirement is to drive opposing actuators in so called 'Master-Slave' mode, whereby the Slave tracks the position of the Master actuator, resulting in unchanged position of the *perceived* specimen centre (**Figure 77**). This pre-supposes the possibility that test frequency will be small enough to neglect the phase lag in Master-Slave response. More importantly, it assumes that specimen strain response will remain uniform throughout the test to serve as an assurance that specimen centre remains coincident with the intersection of the loading axes. The first restricts maximum cyclic load frequency. The second implies that specimen response should remain elastic and without any damage from prior loading. *These two seriously limit the scope of application of conventional planar biaxial test systems, particularly upon the onset of inelastic loading conditions.*

BISS experience with the development and supply of a vast number of biaxial test systems ranging from 250N capacity right up to 4x500 kN systems allowed our scientists to focus on the development of new techniques to allow higher frequency biaxial testing (**Figure 78**) without fear of distorting an ideal biaxial stress state. A patented new adapter practically renders 'floating' condition to the test specimen to retain strictly biaxial stress state even under conditions of non-uniform strain response or specimen centre movement (**Figure 79**). In addition, considerable advances were made in the real-time control firmware on BISS 2370 Octa Series controllers that implement a wide variety of control modes, computed variables by way of Master-Slave load difference and safety limit interlocks to ensure safe biaxial testing at frequencies as high as 50 Hz (**Figure 78**b).



(a) (b)

Figure 78 High speed planar biaxial test system: (a) 50 kN planar biaxial test system at IIT Delhi; (b) specimen failed after applying cyclic load of 50kN (tension/compression) at 25Hz.



(b)

(a)

Figure 79 4 x 500 kN Planar Biaxial System at IISc (a) with patented adapter that renders floating condition to test specimen for retention of strictly biaxial stressing even under non-uniform specimen response.

22. Production Line Shock-Absorber Test Systems

Shock absorber properties are given in terms of force as a function of rod velocity. Ride comfort depends on proper selection of these properties. And shock absorber manufacturers are conscious about the need to ensure that manufactured parts conform to required specifications. Every shock absorber production line is equipped with a shock absorber testing machine armed with the required software and hardware to ensure 100% quality check. These machines often operate three shifts and their reliability can often determine the ability of the manufacturer to meet Just in Time (JIT) demands of automotive manufacturers.

One of the early lessons that we learnt relates to the very mechanics of shock absorber response. Damping force is the sum of friction force and oleo-pneumatic resistance to rod movement. While the latter is sensitive to oil viscosity (temperature), the former is affected by part misalignment during the test. Production testing involves a cycle time of just 7 to 20 seconds and leaves no time to ensure proper alignment of the part. *BISS R&D was able to come up with gripping arrangement that are self-aligning by design and principle of operation.*

*Over two million tests are performed every month on over a hundred BISS shock absorber test stations (**Figure 80**) with practically all globally reputed manufacturers*. Some of these systems are *more than twenty years old and have seen over 50,000 hours of operation*. The evolution of superior shock absorber test technology involved many technological innovations, some of which impacted the entire BISS range of test equipment. The reliability of test equipment benefited from the single board design of the controller. It also benefitted immensely from the BISS innovation of adapting direct drive (DDE) servo-valves in place of the extremely contamination sensitive and expensive two-stage servo-valves used (even to this day) by other test equipment manufacturers. The DDE valves are virtually insensitive to contamination. And as they are

Figure 80 Dual-station shock absorber test system.

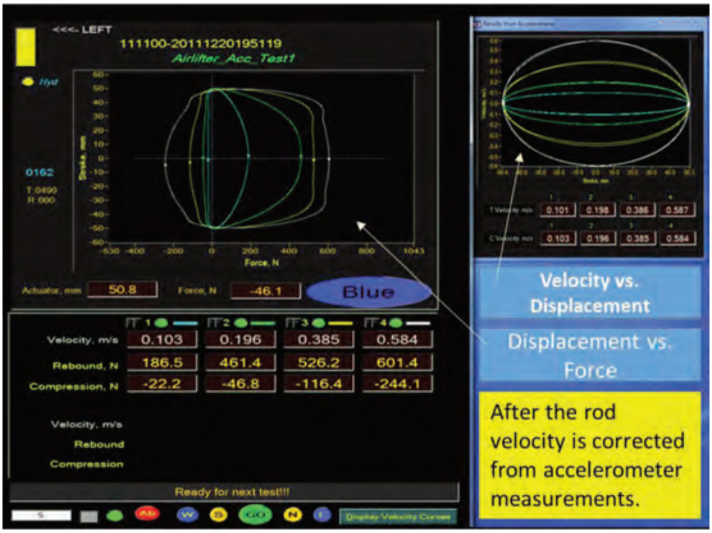
available from multiple vendors, their price is about the same as it would cost to service a 2-stage valve! In terms of linearity and hysteresis of response, they are in fact superior to 2-stage valves! Their only limitation is the frequency ceiling of about 120 Hz, which lies far beyond the envelope of most day-to-day applications of mechanical testing using servo hydraulics.

Two other developments that significantly impacted production line shock absorber testing relate to reliability and energy efficient. These are described below.

Of major concern to customers is the high-energy consumption of servo-hydraulic test systems. Worst affected amongst these are industrial users whose equipment practically operates on a 24/7 basis. Most pumps with flow rates less than about 80 LPM (about 40 kVA power) are of fixed displacement design which implies that all the unused energy must go away by way of heat dissipated into the oil. More energy is then consumed to cool the heated oil! In the late nineties, BISS developed a range of servo-controlled powerpacks (**Figure 81**) over the flow range from 4 to 260 LPM. *The BISS invention involved hydraulic line pressure as feedback to control the speed of rotation of the motor driving the pump.* This essentially meant that only the required amount of oil would be delivered at any given instant. Over the years, several hundred such pumps of new design have been delivered worldwide, effecting a *virtual 'Green Revolution' in servo-hydraulic test technology*. The new pumps are extremely energy efficient. They are also a whole lot quieter and require less cooling capacity than any conventional fixed flow powerpack. The investment cost is recovered from energy savings within a few years of switching over to the new technology.

Figure 81 Servo-controlled power pack.

Returning to the basics of shock absorber testing, damper response depends on instantaneous velocity, while the test itself progresses in displacement control. Thus, it is the first derivative of the parameter being controlled that determines actual damping force readout. The mathematics behind this translation renders the test result extremely sensitive to the fidelity of servo-response. Thus, even if errors in stroke waveform reproduction may be less than 5% at any point, velocity (and therefore, damping force reproduction) may suffer by as much as 10-20%. Such a problem practically does not exist in most mechanical tests where test results are sensitive only to the quality of transducer readout, rather than to the quality of reproduction of desired derivative of the readout. The real-time computing power of BISS controllers was harnessed to enhance the mathematics behind reproducible shock-absorber damping force characterization. Over the years, a variety of techniques have been developed that provide a wide choice of tools to enhance shock-absorber test quality. All BISS shock-absorber production test systems are equipped with linear encoders that deliver noise free, one micron resolution in stroke measurement and control. This extremely high resolution permits real-time computation of instantaneous velocity. There is also the option of installing an accelerometer on the moving grip assembly. The readout from this MEMS transducer is integrated in real-time to deliver velocity readout (**Figure 82**). Such readouts are part of a variety of 'computed readout' channels that can be defined on the control system. They provide the means to not only perform quality tests on shock absorbers, but also provide the tools to maintain such quality by introducing the means for improved reproducibility of required test parameters, even if they are not directly measured from pre-calibrated transducers.



111100-20111220195119

Airlifter_Acc_Test1

Actuator, mm 50.8

Force, N -46.1

	FF 1	FF 2	FF 3	FF 4
Velocity, m/s	0.103	0.196	0.385	0.584
Rebound, N	186.5	461.4	526.2	601.4
Compression, N	-22.2	-46.8	-116.4	-244.1

Ready for next test!!!

	1	2	3	4
T Velocity m/s	0.101	0.198	0.386	0.587
C Velocity m/s	0.103	0.196	0.385	0.584

Velocity vs. Displacement

Displacement vs. Force

After the rod velocity is corrected from accelerometer measurements.

Figure 82 Shock absorber response loops obtained after correcting rod velocity from accelerometer measurements.

As thousands of tests a day may be conducted on the same machine, test results also serve as a diagnostic tool to track production process as well as raw material quality. To serve this purpose, custom software was developed to track the trends of vital parameters (**Figure 83**, **Figure 84** and **Figure 85**) on an hourly as well as daily and weekly basis to alert the production manager to impending issues with input material or process.

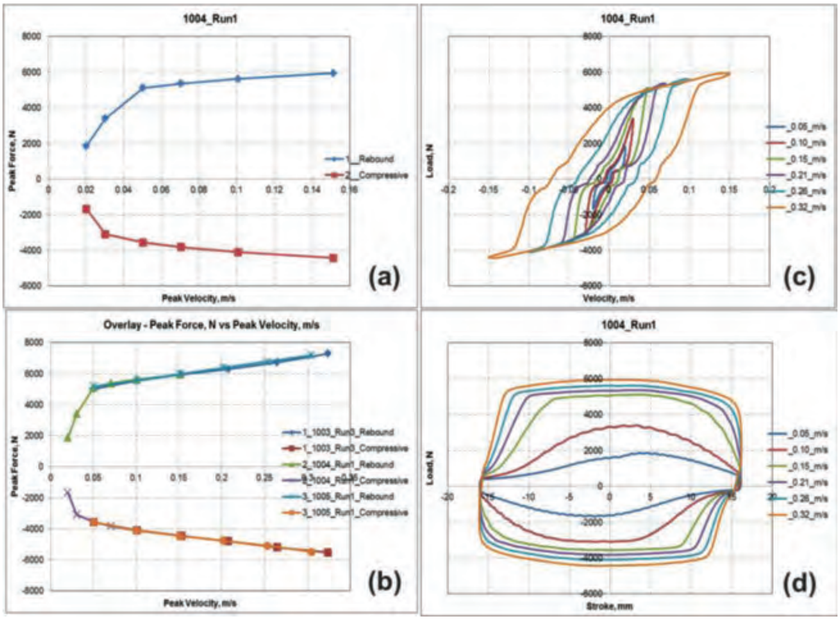
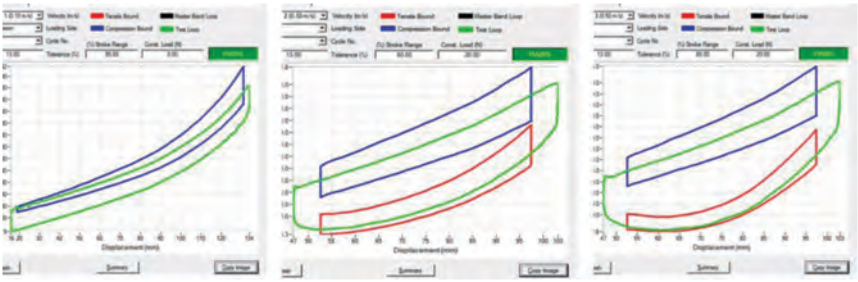


Figure 83 Shock absorber performance test results:(a) peak damping force vs. peak velocity for one run; (b) superposition of peak damping force vs. peak velocity for multiple runs for repeatability check; (c) damping force vs. velocity loops; (d) damping force vs. displacement loops.



(a) (b) (c)

Figure 84 Qualification of shock absorbers by tolerance loop band:(a) spring test cycle; (b) first damping force velocity cycle; (c) second damping force velocity cycle.

(a) (b)

Figure 85 Qualification of shock absorber by acoustic signal:(a) test setup with microphone on the part; (b) FFT signals of good and bad parts compared.

BISS has supplied shock absorber test systems to leading shock absorber manufacturers that have been integrated into completely automated production lines (**Figure 86**). This means the BISS hardware and software have facilitated the automatic loading of assignment, loading/unloading test parts by interacting with third-party robots, placing the Passed and Failed parts in the right bins.

Figure 86 Shock absorber test system in a fully automated production line.

A few variations of BISS shock absorber test systems are shown in **Figure 87**.

(a)

(b)

(c)

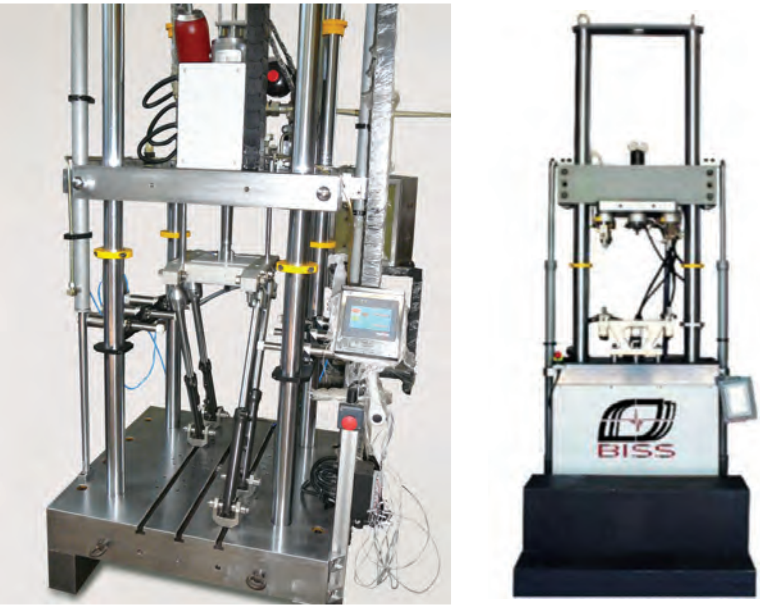
Figure 87 Various versions of shock absorber test systems; (a) System for testing at tilted position; (b) portable single station damper test system; (c) High speed damper test system.

23. High Speed Damper Durability and Performance Test System

Developmental testing of shock absorbersincludes the need for sustained high velocities as high as 4 to 5 m/s for durability testing, high instantaneous speeds of up to 7 m/s and often, the requirement of high response fidelity over a vast velocity range from extremely slow, at less than 0.05 m/s up to over 6 m/s. When parts are continuously stroked at such high velocities, they can rapidly heat up. Cooling arrangements are therefore required with the capability of ensuring acceptable margins of part temperature variation and if required, an automatic hold on the test or slow cycling to cool the oil inside the part. Durability testing of shock absorbers also requires the ability to impose sine-on-sine (heterodyne) waveform. To facilitate cost-effective evaluation of statistical samples, such test systems also demand the ability to test multiple parts, with the ability to independently track the damping force response of individual parts. Finally, arrangements are called for to apply controlled side loads to simulate actual operating conditions. *Practically none of the test systems used in conventional materials characterization carries such diverse requirements in terms of performance, that carry with them unusual demands on test system design and performance.*

To deliver the required performance, BISS builds hydraulic powerpacks with between 250 and 500 LPM flow, rated for continuous indefinite operation. Closed loop thermostatic cooling is employed on individual parts being tested. Special light weight grips cut from high strength Al-alloys are built to withstand over 20g acceleration experienced in high frequency long stroke cycling to achieve the rated velocities. To reduce vibrations, the weight of the load frame assembly is increased using deadweights and the whole system is placed on oleo-pneumatic dampers for vibration isolation. With such a huge collection of parts moving continuously at high speed, all moving fasteners are wire-locked, just like in aircraft and protective caging with safety interlocks employed to prevent damage or injury. Of course, all the special technologies associated with control and measurement that are employed on production test systems (***Figure 88***) are also deployable on these test systems.

Special mention is due about a technological breakthrough at BISSthat overcomes the inherent shortcoming of multi-stage servovalves. Such servovalves can deliver from over 200 to as much as 1000 LPM flow, which is made possible by the use of cascaded stages of spools that make hysteresis, lag and non-linearity practically inevitable. BISS controllers boast of unique firmware algorithms built into the control loop that linearise even a non-linear servo-valve so that system response is good even when viewed in terms of velocity, the ‘capricious’ first derivative of displacement! The linearizationprocess is essentially involves controller firmware ‘studying’ how individual servolvalves deviate from the required linear response and then building servo-output transfer functions that will account for such deviation. As this happens in real-time, the algorithms can ‘adjust’ to potential deterioration in servo-valve performance as well, thereby ensuring that the quality of test results is not compromised. **Figure 89** shows the actuator velocity vs. servo input before and after correction for a servo valve with nonlinear response. **Figure 90** and **Figure 91** show the quality of displacement and velocity against their desired value respectively before and after linearization of servo valve response.



(a) (b)

Figure 88 High speed shock absorber (damper) test system: (a) 6.5 m/s damper test system with 4-parts fixture, adjustable part inclination; (b) 4.0 m/s damper test system with 6-parts fixture.

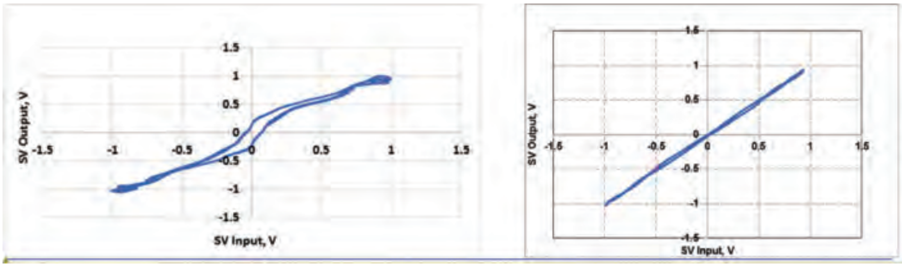
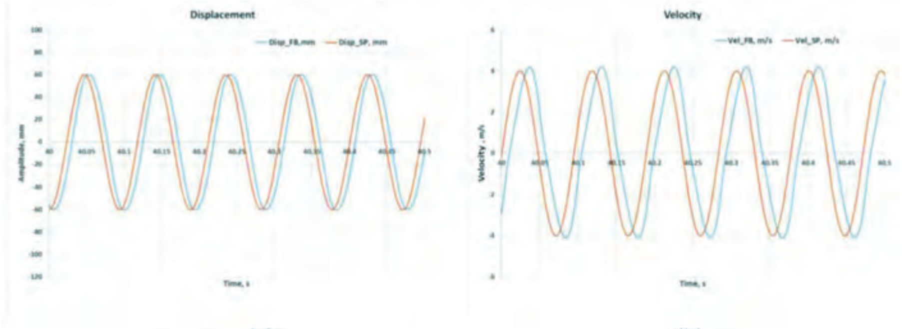
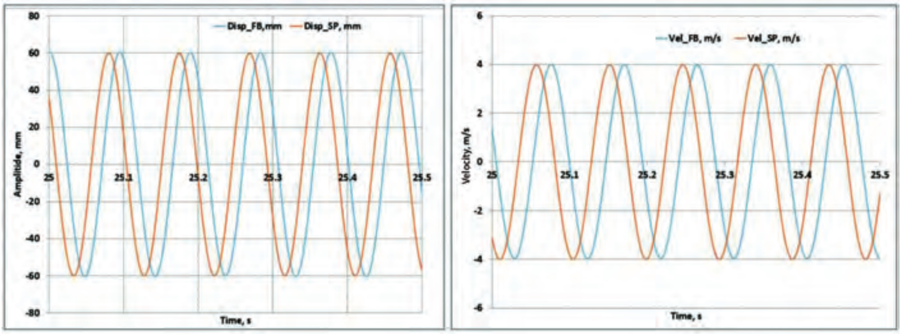


Figure 89 Servo output (actuator velocity corrected for lag) vs. Servo input: (a) nonlinear servo response;(b) linearized servo response after correction through firmware. System performance shows considerable improvement with this correction.



(a) (b)

Figure 90 System response before correction for nonlinear servo valve response: (a) actuator displacement: command and feedback; (b) actuator velocity: command and feedback.



(a) (b)

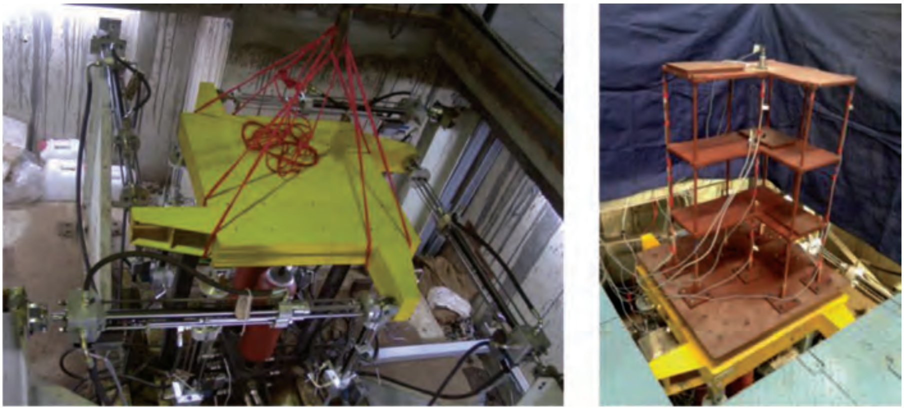
Figure 91 System response after correction for nonlinear servo valve response:(a) actuator displacement: command and feedback; (b) actuator velocity: command and feedback. Note that now velocity feedback precisely matches with command.

24. Shake Tables for Earthquake Simulation

The devastation wrought by earthquakes depends not as much on the magnitude of the event, as on the degree of resistance to earthquakes engineered into civil structures. The threat of consequential damage in the case of nuclear power reactors makes earthquake engineering of prime importance in their design and also in the certification of equipment used in such reactors as their continued functionality may be critical to operational safety in the event of an earthquake.

Earthquakes are three dimensional by nature. They induce oscillations in all six possible ways – three linear and three rotational. Realistic laboratory simulation of earthquakes demands 3-axis, 6 Degree-of-Freedom (6DOF) shake table movement. As gravity is a major component of loading, earthquake shake tables are driven by eight actuators, with as many as four of them oriented along the vertical axis. This poses many technological obstacles that few companies worldwide (*BISS is amongst the select few*) have been able to overcome. The first problem is a mathematical one. For any linear or angular movement of the table in space, the precise displacement of each of the eight actuators is computed by solving a system of eight linear equations. This operation needs to be performed in real time and the actuator positions updated simultaneously, several thousand times a second to ensure smooth table movement according to the desired time history. In the process, a peculiar problem specific to 8-actuator systems can 'spoil the party': As two extra actuators are involved than the required six degrees of freedom, inaccuracy in actuator movement can lead to severe internal loads proportional to the product of system stiffness and actuator stroke error. This is a consequence of physical constraint in a tightly coupled system, much like the consequence of forcing all four legs of a dining table or chair to touch the ground, when one of the legs is a bit shorter or longer than it should be. Not surprisingly, earthquake shake tables represent the ultimate in precision and performance of a multi-actuator servo-hydraulic system.*Suffice to state that less than half a dozen vendors worldwide have mastered this technology.*

The BISS team devoted some twenty years of R&D in shake-table development in close collaboration with the Indian Institute of Science (IISc). **Figure 92** shows the first triaxial shake table built by BISS at IISc in 2004. BISS shake tables have been the subject or platform of several PhD theses. The result is a mature modular shake table (**Figure 93**) design that serves numerous laboratories worldwide. The incorporation of digital linear encoders has rendered unprecedented 'ppm level' resolution in dynamic actuator stroke readout and control as seen on the one meter uniaxial shake table at IIT Guwahati (**Figure 94**). Such quality permits velocity and acceleration as computed channels from stroke feedback. Additionally, the 2370MS controllers provide for data acquisition from multiple accelerometers, strain gauges and other transducers on the table and test object. For applications in education in earthquake engineering, a compact 'desk top' servo-electric shake table (**Figure 95**) capable of uniaxial reproduction of earthquakes is available. A comprehensive package of application software is available for reproduction of practically any time history of interest, for time and frequency domain data analysis (**Figure 96**). BISS shake tables can be coupled with structural actuators and with numerical models of structures to perform state-of-the-art hybrid simulation studies.



(a) (b)

Figure 92 3-axes, 6-dofs Shake table at IISc: (a) overview; (b) setup for experimental reliability analysis.

Figure 93 Modular triaxial shake table.

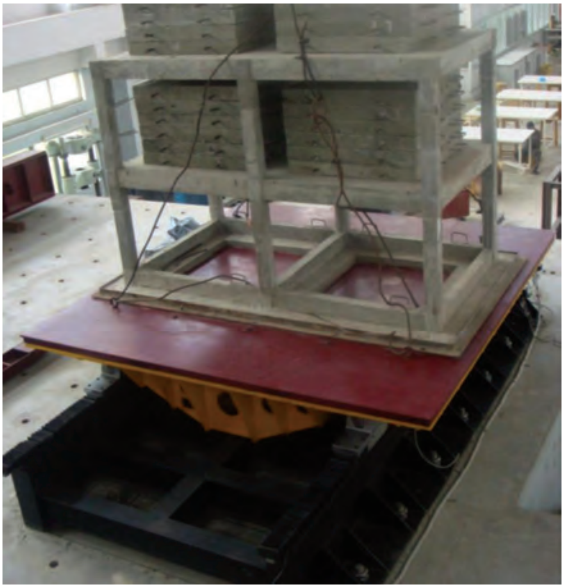


Figure 94 Uniaxial shake table (5 tons capacity, 1000 mm stroke with resolution of 1 micron) at IIT Guwahati.

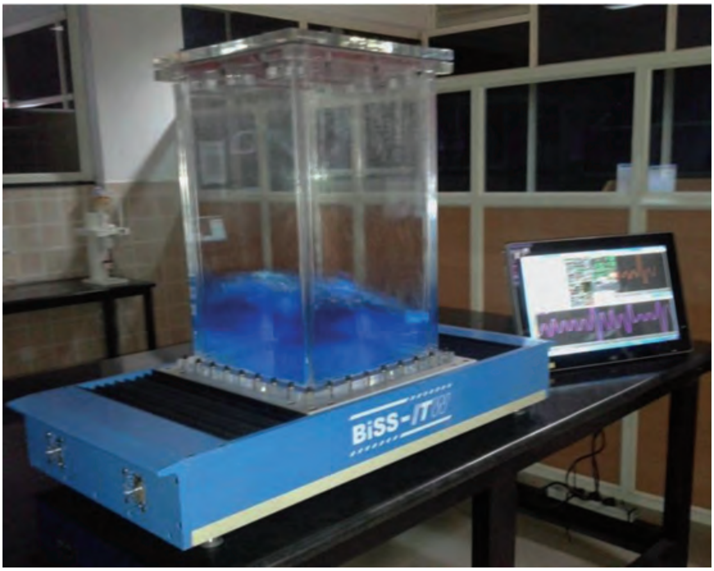
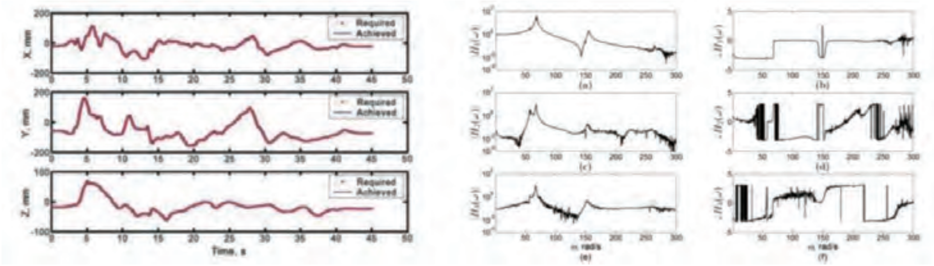


Figure 95 Desktop uniaxial servo-electric shake table.



(a) (b)

Figure 96 Shake table support excitations and responses:
(a) El Centro 3-component earthquake displacement input excitations (Time histories);
(b) Frequency response functions of structural responses.

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