Safety and Reliability

While various structural failures have captured national attention over the years, the events of September 11, 2001 generated a greatly increased awareness of vulnerabilities in our national infrastructure. The extent of these vulnerabilities depends to a large degree on the performance of materials in situations outside of the original design considerations. It is now recognized that a critical and urgent national need exists to establish the behavior of materials under such extreme loadings, and to disseminate guidance and tools to assess and reduce future vulnerabilities.

The goal of providing a technical basis for cost-effective changes to national practices and standards, coupled with a need for an integrated effort drawing on capabilities and expertise of a broad collaborative team, has lead to the development of the Safety and Reliability Program within MSEL. This program draws on the expertise of several divisions in MSEL and across NIST.

Project selection is guided by an identification and assessment of the particular vulnerabilities within our materials-based infrastructure, and focusing on those issues which would benefit strongly by improved measurements, standards, and materials data. Ultimately, we intend to moderate the effects of acts of terrorism, natural disasters, or other emergencies, all through improved use of materials.

Our vision is to be the key resource within the Federal Government for materials metrology development as realized through the following objectives:

- Identify and address vulnerabilities and needed improvements in U.S. infrastructure
- Develop and deliver standard measurements and data;
- Develop advanced measurement methods needed by industry to address new problems that arise with the development of new materials;
- Support other agency needs for materials expertise.

This program responds both to customer requests (primarily other government agencies) and to the Department of Commerce 2005 Strategic Goal of "providing the information and framework to enable the economy to operate efficiently and equitably." For example, engineering design can produce safe and reliable structures only when the property data for the materials is available and accurate. Equally importantly, manufacturers and their suppliers need to agree on how material properties should be measured.

The Safety and Reliability Program works toward solutions to measurement problems on scales ranging from the macro to the micro, in three of the Laboratory's Divisions (Materials Reliability, Metallurgy, and Polymers). The scope of activities includes the development and innovative use of state-of-the-art measurement systems; leadership in the development of standardized test procedures and traceability protocols; development of an understanding of materials in novel conditions; and development and certification of Standard Reference Materials (SRMs). Many of the tests involve extreme conditions, such as high rates of loading, high temperatures, or unusual environments (*e.g.*, deep underwater). These extreme conditions often produce physical and mechanical properties that differ significantly from the handbook values for their bulk properties under traditional conditions. These objectives will be realized through innovative materials, property measurement and modeling.

The MSEL Safety and Reliability Program is also contributing to the development of test method standards through committee leadership roles in standards development organizations such as the ASTM International and the International Standards Organization (ISO). In many cases, industry also depends on measurements that can be traced to NIST Standard Reference Materials (SRM®).

In addition to the activities above, all three divisions provide assistance to various government agencies on homeland security and infrastructural issues. Projects include assessing the performance of structural steels as part of the NIST World Trade Center Investigation, advising the Bureau of Reclamation on metallurgical issues involving pipelines and dams, advising the Department of the Interior on the structural integrity of the U.S.S. Arizona Memorial, and collaborating with both the Department of Transportation and the Department of Energy on pipeline safety issues.

Table of Contents

Safety and Reliability

Materials Reliability

Metallurgy

Polymers

Infrastructure Reliability: Analysis of Structural Steel in the World Trade Center

In 2002 NIST became the lead agency in the investigation of the World Trade Center collapse. The investigation addresses many aspects of the catastrophe, from occupant egress to factors affecting how long the Twin Towers stood after being hit by the airplanes, with a goal of gaining valuable information for the future. A critical aspect of the investigation is the metallurgical analysis of structural steels from the Twin Towers. The analysis includes characterization of properties, failure modes, and temperature excursions seen by the steel.

Stephen W. Banovic, Richard J. Fields, Timothy J. Foecke, William E. Luecke, J. David McColskey, Christopher N. McCowan, Thomas A. Siewert, and Frank W. Gayle

The collapse of the World Trade Center (WTC) Towers on September 11, 2001, was the worst building disaster in human history. Engineers, emergency responders, and the nation were largely unprepared for such a catastrophe. NIST is investigating the disaster (see **http://wtc.nist.gov/**), and a primary objective is to determine why and how the towers collapsed after the initial impact of the aircraft. As part of this investigation, the Metallurgy and Materials Reliability Divisions in MSEL are studying recovered structural steel from the WTC site. Progress in this study is outlined here.

Task 1 — Collect and catalog physical evidence: 236 structural pieces of the WTC towers have been collected, brought to NIST and studied. Reports have been issued documenting the steel, the as-built locations, the structure of the towers based on design documents, and the standards at the time of construction.

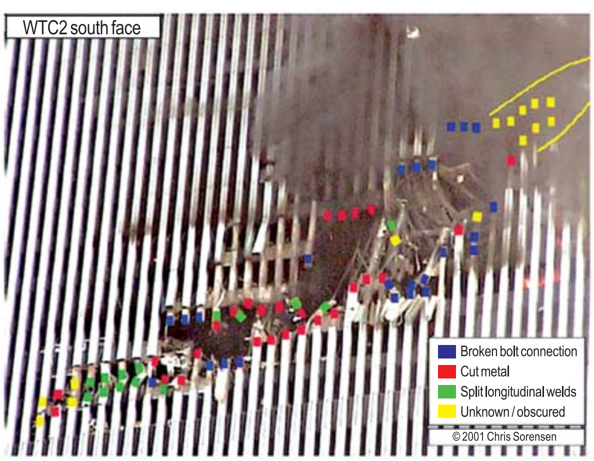

Figure 1: Enhanced image of the impact zone of WTC 2 has allowed determination of failure modes in the perimeter columns.

Task 2 — Categorize failure mechanisms based on visual evidence: Available photographic evidence and recovered steel have been examined and documented as to failure mechanisms (Figure 1).

Task 3 — Determine steel properties to support structure performance and airplane impact modeling studies: 29 different steels have been characterized for room temperature mechanical properties. High-temperature and high-strain-rate tests are now complete. Creep, or time–temperature-dependent behavior, has been determined for floor truss and column steel.

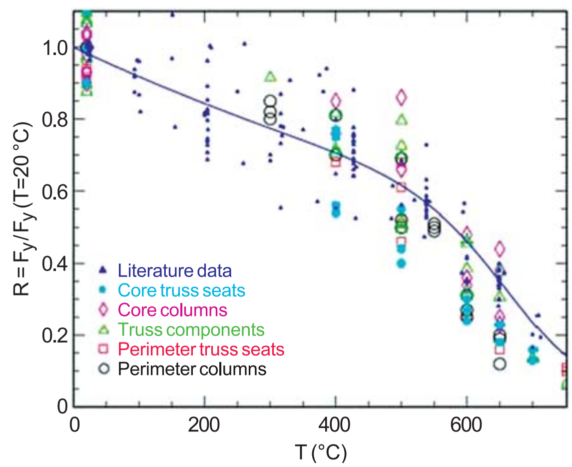

Figure 2: Normalized yield strength and ultimate tensile strength measured as function of temperature. Model curve is based on historical data for WTC era steels.

Task 4 — Correlate determined steel properties with specified properties: Most steel was found to exceed the specified minimum values by 5 to 10 percent.

Task 5 — Analyze steel to estimate temperature extremes: We have developed a technique of paint characterization to provide a quick mapping of temperature excursions seen by the steel. Challenges included deciphering pre- and post-collapse exposure (see related Highlight in this report).

Data on material properties have been provided to aid in the modeling of plane impact and structural response to the fires. A final draft of the investigation report will be released for public comment in December 2004.

Contributors and Collaborators

R. Santoyo, L. Rodine (Materials Reliability Division, MSEL, NIST); M. Williams, S. Claggett, M. Iadicola, R. Jiggetts (Metallurgy Division, MSEL, NIST)

Infrastructure Reliability: Standard Test Methods for Fire-Resistant Steel

The fires in the World Trade Center and the ensuing collapse focused attention on the vulnerability of structural steel to fire. Recently, steel mills in Europe and Japan have begun to market steels designated as "fire-resistant." This project is developing a standard test method for quantitatively evaluating and comparing the resistance to high-temperature deformation and failure of structural steels.

William E. Luecke, J. David McColskey, Richard J. Fields, and Frank W. Gayle

At room temperature, the stress–strain behavior of structural steel is considered to be independent of time. Above about 300 °C, structural steel begins to lose strength. At still higher temperatures, about 500 °C, creep, or time-dependent deformation, further reduces the load-carrying capability. By 600 °C, most structural steels have lost more than half their strength. For this reason, structural steels in buildings are insulated to minimize the temperature rise and resulting strength loss.

Fire resistant (FR) steels are intended to be drop-in replacements for structural steel. They typically meet the same specifications with similar welding properties and cost only marginally more. Yet these steels retain superior high-temperature strength, offering potential for extra time for building occupants to escape a fire.

In Japan and Europe, FR steels are qualified based on yield strength retention at high temperature. This definition may not be the most appropriate since retained yield strength is a short-time property, yet fire-resistance is often measured in hours. Also, with increasing temperature, strength becomes increasingly sensitive to the strain rate. Current U.S. standards for load-bearing components in fire are based on time to reach a given temperature, so effectively all steels are considered to have the same high-temperature strength reduction, regardless of actual properties.

We are currently studying a hybrid of creep and conventional tension tests. The test specimen is held under constant load as the test temperature ramps upward linearly. Over a narrow temperature range, which can be approximated as a critical temperature, the deformation rate increases dramatically, and the specimen fails. This critical temperature can be used as a measure of fire resistance.

One goal of this project is to refine this test technique and offer it as a draft standard. Published research has established that the temperature ramp test can rank steels, but definitive studies comparing ordinary and FR steels are lacking. Until a standard test method is developed, it is difficult to confidently compare results between laboratories. This research will focus on understanding the limitations, repeatability, and reproducibility of the method by characterizing several different classes of construction steels. Interlaboratory studies will be used to probe the method's limitations, precision and bias.

A second goal is to generate constitutive models for modeling high-temperature deformation of steels. If test results are not predictable from underlying deformation behavior, a test cannot possibly indicate real-world performance. A second benefit is that much-needed data will be supplied for finite element modeling of modern structural steel deformation in fire, a prerequisite for performance-based fire resistant design.

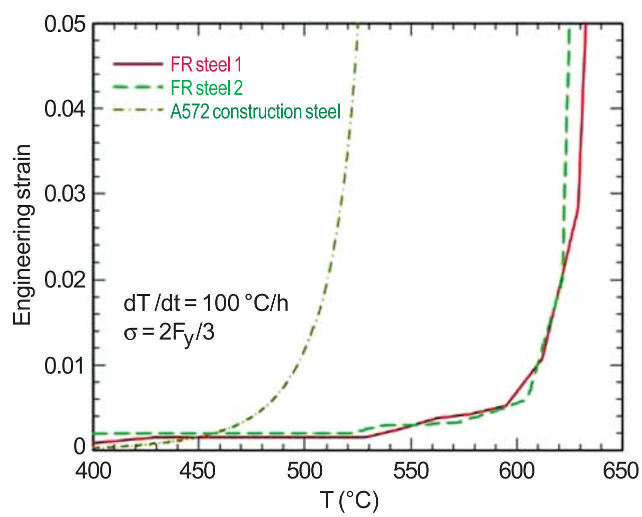

Figure 1: *Comparison of "run-away creep" deformation of FR and ordinary construction steel.*

Figure 1 illustrates the concept of critical temperature for "run-away" creep for two FR steels and one conventional construction steel. The results demonstrate the potential performance advantage of FR steel. Much more work is necessary, however, to understand the variability in performance of ordinary and FR steels.

During 2004, we also spearheaded the development of an ASTM task group under committee A01 to evaluate test methods for fire resistance of structural steel.

Contributors and Collaborators

M. Bykowski (SURF)

Infrastructure Reliability: Waveform-Based Acoustic Emission

The major project objective is to develop the scientific underpinnings necessary to enhance acoustic emission (AE) technology through increased, high-sensitivity bandwidth. Current secondary objectives include: (1) developing for many users the missing element of modeling AE signals for multiple sources in specimens with and without edge reflections; and (2) developing rational approaches to analyze AE waveforms to solve the real-world problems of reliable identification and location of sources of AE signals.

Thomas A. Siewert and Marvin Hamstad

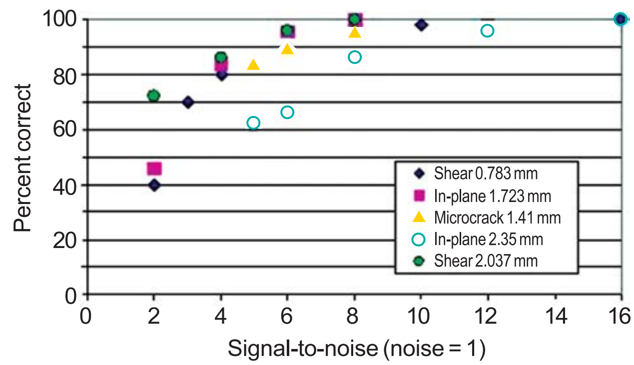

Figure 1: *Percent of trials out of 50 with correct source identification versus S/N ratio for the source types and depths listed.*

Technical Description

Acoustic emission (AE) refers to the generation of propagating elastic displacement waves as a result of micro-sized transient-energy releases in a material. Monitoring these waves can provide fundamental information about the location and mechanism(s) of the transient-energy release as well as the time/stress history of such releases. The technical approach, which is beyond that currently commercially offered for either resonant or waveform-based AE technology, is to develop all the key components relevant to a wideband application of AE technology. These include development of wideband high-sensitivity sensor/preamplifiers; high-speed digital recording data-gathering systems of wide dynamic range; finite-element modeling (FEM) to predict near- and far-field displacement waves from AE sources in large and small specimens; wideband experimental AE displacement waveforms from sources in materials of interest; signal-processing techniques to accurately identify source types and their locations; and experimental characterizations of simulated AE wave propagation. The scope in FY2004 covered studies on the effects of electronic background noise on the identification of AE source types through the use of modal amplitudes obtained from wavelet-transform (WT) results.

Accomplishments

Previous work, with FEM-generated signals, demonstrated a technique to identify AE sources by using ratios of modal magnitudes in two different radiation directions. The finite-element code modeled AE signals for dipole-type sources in an aluminum plate 4.7 mm thick. The plate had transverse dimensions sufficient that plate edge reflections did not superimpose on direct signal arrivals. The FEM signals were essentially noise free.

To examine how the presence of electronic noise (from the sensor/preamplifier) alters the ability to correctly identify AE source types, detailed analysis was carried out by superimposing experimental wideband noise on the FEM-based AE signals. Important discoveries were made. The WTs of typical noise signals demonstrated that the WT magnitudes of the noise at each frequency vary with time in a random fashion. Hence, it was necessary to do a statistical study of the effects of noise. Fifty noise segments were prepared. The noise segments were added to the noise-free FEM signals. At each signal-to-noise (S/N) ratio, fifty FEM-plus-noise signals were used for each source type (in-plane dipole, micro-crack initiation, and shear without a moment). The S/N ratio was calculated based on the peak signal amplitude in the assumed direction of applied stress for the three source types. Using the same successful technique for noise free signals, the FEM-plus-noise signals were processed. Figure 1 shows how the number of correct source identifications depends on the S/N ratio. Clearly a S/N ratio of at least six to one is needed to correctly identify a large percentage of the source types. It is expected that all modal amplitude techniques of source identification will be similarly affected. Close examination of the WTs of the noise and the AE signals revealed that the noise signals inhabit the same frequency ranges as the AE signals; hence it will not be straightforward to filter out the noise signals.

Contributors and Collaborators

NIST participants: D. McColskey (Materials Reliability Division, NIST); Cross OU collaborators: A. O'Gallagher, J. Gary (Information Technology Laboratory, NIST); W. Prosser (NASA Langley)

Infrastructure Reliability: Charpy Impact Machine Verification

We assist owners of Charpy impact machines in achieving conformance with the requirements of ASTM Standard E 23. We interact with the ASTM Committee responsible for the Charpy impact standard to improve the service and to maintain a high-quality verification program. We also participate in the activity in ISO Committee TC 164, so our specimens and procedures remain compatible with the associated international and regional standards.

Thomas A. Siewert

Technical Description

The Charpy impact test uses a swinging hammer to assess the resistance of a material to brittle fracture. The absorbed energy is measured from a calibrated scale, encoder, and/or an instrumented striker. The low cost and simple configuration of the test have made it a common requirement in codes for critical structures such as pressure vessels and bridges. This project is handled jointly by the Standard Reference Materials Program (of the Office of Measurement Services), which oversees the administrative aspects of the program, and the Materials Reliability Division, which handles the technical and verification aspects. NIST provides highly characterized standard reference materials (SRMs) to machine owners and independent calibration services, then evaluates the results of tests of these specimens on their impact machines. Owners of machines that meet the requirements of ASTM Standard E 23 are given a letter of conformance, while owners of nonconforming machines are given recommendations on corrective actions. Our special facilities include three master Charpy impact machines (all 300 J to 400 J capacity). These three machines are used to establish certified values for the NIST reference materials sold through the Standard Reference Materials Program Office. In addition, we have several more machines (3 J to 400 J capacities) that are used for research purposes.

Accomplishments

We expect about 950 customers for this service in FY04, a number similar to the customer base in recent years. The great majority of these machines were within tolerances required by ASTM Standard E 23. As usual, many customers took advantage of our support services, as shown by over 674 emails, 730 faxes, and 500 phone calls in the first 9 months of FY04. We immediately contact the machine owner when it fails to meet the verification criteria. In this contact (by phone, mail, email, or fax), we suggest corrective measures.

One big change this year was that Dan Vigliotti retired after serving as Charpy Coordinator for about 12 years. Ray Santoyo has completed his training for this position and has taken over as Charpy Coordinator. We have just completed a three-year test program that is collecting data on “International Master Batches” of Charpy impact verification specimens. A meaningful harmonization (equivalency) of Charpy V-notch standards around the world is unlikely until the reference materials used for the verification of impact machines in Europe, Japan, and the United States (EN-10045-2, JIS B 7722, and ASTM E 23) share a more common method of certification. The results of this test program are being used to evaluate the use of Master Specimens as a common control in the certification procedure for CVN verification specimens between the three countries’ National Measurement Institutes. It will also evaluate machine variables, offsets, uncertainty, and other factors relevant to the harmonization of our respective systems. Initial results indicate the equivalency of the energy scales used to measure absorbed energy by the United States, Europe, and Japan.

We are helping to organize another international symposium, “Second Symposium on Pendulum Impact Machines: Procedures and Specimens,” to be held in conjunction with the November 2004 meeting of ASTM Committee E 28 in Washington, D.C. Previous symposia have provided valuable insight into improvements in our program.

This year, we dedicated a previous Charpy master machine to Izod impact testing, and expect to produce a new SRM in FY05.

Chris McCowan serves as the Chairman of ISO TC164 SC4 P, on pendulum impact and also as the Chairman of ASTM Subcommittee E28.07 on impact testing.

Contributors and Collaborators

NIST participants: Ray Santoyo (Charpy Program Coordinator), C. McCowan, T. Siewert, J. Clark, D. Cyr, C. Dewald, S. Vincent, N. Neumeyer, J. Percell; External collaborators: IRMM (Europe), NRLM (Japan), Members of ASTM Subcommittee E 28.07

Analysis of Structural Steel in the World Trade Center

In 2002 NIST became the lead agency in the investigation of the World Trade Center collapse. The investigation addresses many aspects of the catastrophe, from occupant egress to factors affecting how long the Twin Towers stood after being hit by the airplanes, with a goal of gaining valuable information for the future. A critical aspect of the investigation is the metallurgical analysis of structural steels from the Twin Towers. The analysis includes characterization of properties, failure modes, and temperature excursions seen by the steel.

Stephen W. Banovic, Richard J. Fields, Timothy J. Foecke, William E. Luecke, J. David McColskey, Christopher N. McCowan, Thomas A. Siewert, and Frank W. Gayle

The collapse of the World Trade Center (WTC) Towers on September 11, 2001, was the worst building disaster in human history. Engineers, emergency responders, and the nation were largely unprepared for such a catastrophe. NIST is investigating the disaster (see **http://wtc.nist.gov/**), and a primary objective is to determine why and how the towers collapsed after the initial impact of the aircraft. As part of this investigation, the Metallurgy and Materials Reliability Divisions in MSEL are studying recovered structural steel from the WTC site. Progress in this study is outlined here.

Task 1 — Collect and catalog physical evidence: 236 structural pieces of the WTC towers have been collected, brought to NIST and studied. Reports have been issued documenting the steel, the as-built locations, the structure of the towers based on design documents, and the standards at the time of construction.

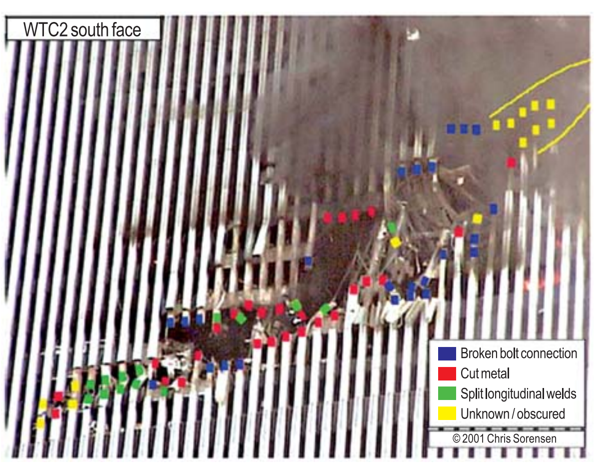

Figure 1: *Enhanced image of the impact zone of WTC 2 has allowed determination of failure modes in the perimeter columns.*

Task 2 — Categorize failure mechanisms based on visual evidence: Available photographic evidence and recovered steel have been examined and documented as to failure mechanisms (Figure 1).

Task 3 — Determine steel properties to support structure performance and airplane impact modeling studies: 29 different steels have been characterized for room temperature mechanical properties. High-temperature and high-strain-rate tests are now complete. Creep, or time–temperature-dependent behavior, has been determined for floor truss and column steel.

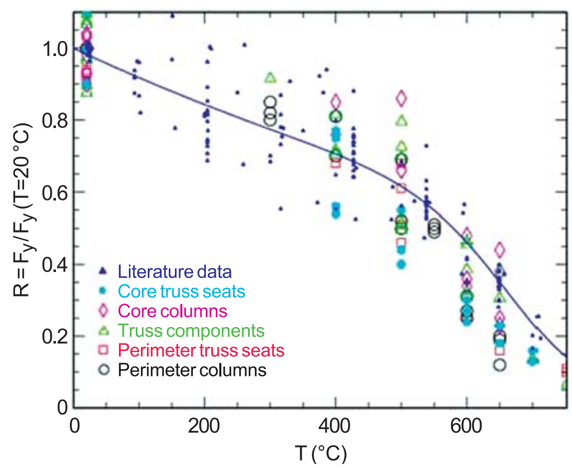

Figure 2: *Normalized yield strength and ultimate tensile strength measured as function of temperature. Model curve is based on historical data for WTC era steels.*

Task 4 — Correlate determined steel properties with specified properties: Most steel was found to exceed the specified minimum values by 5 to 10 percent.

Task 5 — Analyze steel to estimate temperature extremes: We have developed a technique of paint characterization to provide a quick mapping of temperature excursions seen by the steel. Challenges included deciphering pre- and post-collapse exposure (see related Highlight in this report).

Data on material properties have been provided to aid in the modeling of plane impact and structural response to the fires. A final draft of the investigation report will be released for public comment in December 2004.

Contributors and Collaborators

R. Santoyo, L. Rodine (Materials Reliability Division, MSEL, NIST); M. Williams, S. Claggett, M. Iadicola, R. Jiggetts (Metallurgy Division, MSEL, NIST)

Standard Test Methods for Fire-Resistant Steel

The fires in the World Trade Center and the ensuing collapse focused attention on the vulnerability of structural steel to fire. Recently, steel mills in Europe and Japan have begun to market steels designated as "fire-resistant." This project is developing a standard test method for quantitatively evaluating and comparing the resistance to high-temperature deformation and failure of structural steels.

William E. Luecke, J. David McColskey, Richard J. Fields, and Frank W. Gayle

At room temperature, the stress–strain behavior of structural steel is considered to be independent of time. Above about 300 °C, structural steel begins to lose strength. At still higher temperatures, about 500 °C, creep, or time-dependent deformation, further reduces the load-carrying capability. By 600 °C, most structural steels have lost more than half their strength. For this reason, structural steels in buildings are insulated to minimize the temperature rise and resulting strength loss.

Fire resistant (FR) steels are intended to be drop-in replacements for structural steel. They typically meet the same specifications with similar welding properties and cost only marginally more. Yet these steels retain superior high-temperature strength, offering potential for extra time for building occupants to escape a fire.

In Japan and Europe, FR steels are qualified based on yield strength retention at high temperature. This definition may not be the most appropriate since retained yield strength is a short-time property, yet fire-resistance is often measured in hours. Also, with increasing temperature, strength becomes increasingly sensitive to the strain rate. Current U.S. standards for load-bearing components in fire are based on time to reach a given temperature, so effectively all steels are considered to have the same high-temperature strength reduction, regardless of actual properties.

We are currently studying a hybrid of creep and conventional tension tests. The test specimen is held under constant load as the test temperature ramps upward linearly. Over a narrow temperature range, which can be approximated as a critical temperature, the deformation rate increases dramatically, and the specimen fails. This critical temperature can be used as a measure of fire resistance.

One goal of this project is to refine this test technique and offer it as a draft standard. Published research has established that the temperature ramp test can rank steels, but definitive studies comparing ordinary and FR steels are lacking. Until a standard test method is developed, it is difficult to confidently compare results between laboratories. This research will focus on understanding the limitations, repeatability, and reproducibility of the method by characterizing several different classes of construction steels. Interlaboratory studies will be used to probe the method's limitations, precision and bias.

A second goal is to generate constitutive models for modeling high-temperature deformation of steels. If test results are not predictable from underlying deformation behavior, a test cannot possibly indicate real-world performance. A second benefit is that much-needed data will be supplied for finite element modeling of modern structural steel deformation in fire, a prerequisite for performance-based fire resistant design.

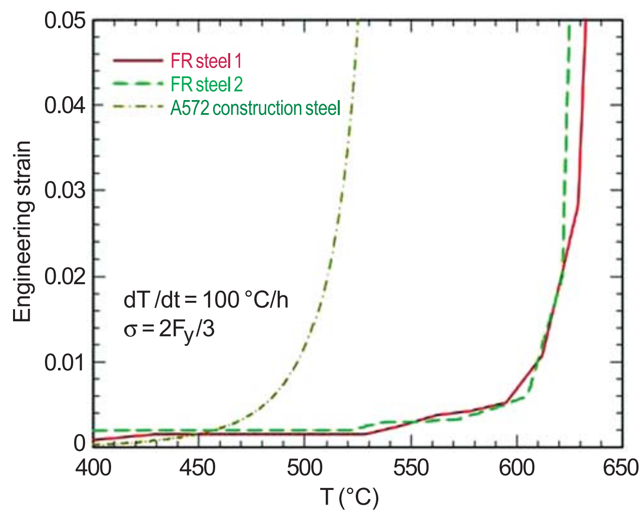

***Figure 1:** Comparison of "run-away creep" deformation of FR and ordinary construction steel.*

Figure 1 illustrates the concept of critical temperature for "run-away" creep for two FR steels and one conventional construction steel. The results demonstrate the potential performance advantage of FR steel. Much more work is necessary, however, to understand the variability in performance of ordinary and FR steels.

During 2004, we also spearheaded the development of an ASTM task group under committee A01 to evaluate test methods for fire resistance of structural steel.

Contributors and Collaborators

M. Bykowski (SURF)

Pipeline Safety: Corrosion, Fracture, and Fatigue

A critical element of the nation's infrastructure is the more than 2 million miles of natural gas and hazardous liquid pipelines that provide over half of the nation's energy. While pipelines are the safest means of transporting these materials, they are not immune to failures. In 2002, Congress passed the Pipeline Safety Improvement Act to reduce pipeline failure rates, increase public safety, and ensure a continuous and uninterrupted delivery of the nation's energy supply. NIST is working with the pipeline industry, DoT, and DoE to provide the measurement methods, standards, and data needed to accomplish this objective.

Richard E. Ricker

In December 2002, Congress passed the Pipeline Safety Improvement Act (PSIA), through which the DoT Office of Pipeline Safety (DoT/OPS), DoE, and NIST will coordinate pipeline R&D. In FY 2004, DoT/OPS, DoE, and NIST signed a memorandum of understanding (MOU) and a Five-Year Joint R&D Plan detailing agency responsibilities in a program of research, development, demonstration, and standardization for pipeline integrity. The Department of the Interior/MMS has also been included in the plan because of its responsibility for off-shore oil pipelines. Under these agreements, NIST is responsible for materials research, fire safety, and standards development that pertain to pipeline safety, reliability, and damage prevention.

A number of factors have combined to increase the need for improvements in the safe operation of pipelines. Among these are increases in national energy needs,

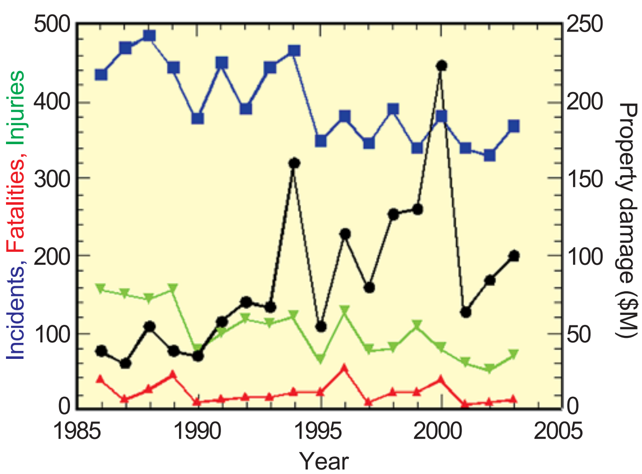

Figure 1: Pipeline incidents and damage since 1986 (DoT/OPS).

population densities near pipelines, environmental concerns, and average pipeline age. While recent accidents have brought increased attention to this issue, pipeline incident rates have not changed significantly since 1986 (Figure 1). While failure mechanisms are not always thoroughly documented, the DoT/OPS incident data can be used to estimate the distribution of failure mechanisms (Figure 2). Clearly, fracture, fatigue and corrosion account for a significant proportion of the failures. Understanding and developing better standards for preventing these materials-related failure mechanisms is the objective of NIST R&D in 2004–2005 project.

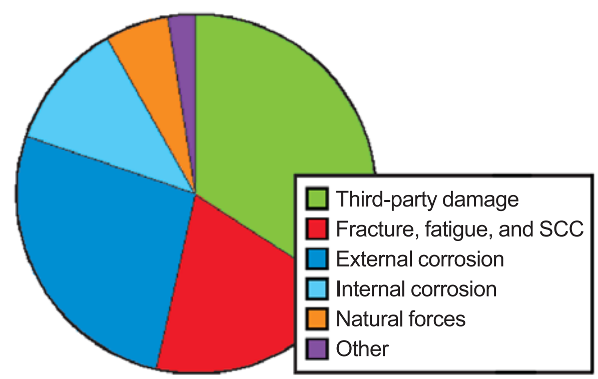

***Figure 2:** Estimated pipeline failure mechanism distribution based on DoT/OPS data over ≈ 10 years.*

NIST has a history of contributions to pipeline safety. For example, NIST conducted welding and fracture research for the Alaskan pipeline, and the NIST 14-year study of underground corrosion is the basis for several current pipeline standards. The current program will review existing standards, the current corrosion, fatigue, and fracture issues, and evaluate where improvements may be possible. This work will be done in collaboration with industry, particularly the Pipeline Research Council International (PRCI) Corrosion and Inspection Technical Committee, and with private sector consensus standards setting organizations. NIST and its collaborators have discussed and reviewed NIST R&D plans and coordination. A Government/Industry Pipeline R&D Forum is being organized for April 2005 to present the Five-Year Joint R&D Plan.

Contributors and Collaborators

R.J. Fields, T.J. Foecke, F.W. Gayle, C.A. Handwerker (Metallurgy Division, NIST); T. Siewert, C. McCowan (Materials Reliability Division, NIST); C. Sames (PRCI); J. Merritt, S. Gerard, R. Smith (DoT/OPS); C. Freitas, R. Anderson, D. Driscoll (DoE); M. Else (DoI)

Frangible Bullets and Soft Body Armor

Police officers' lives often depend upon the effectiveness of their soft body armor. Continued introduction of new types of body armor and bullets (including lead-free frangible models) are overwhelming the enforcement community's ability to test everything adequately. At the request of the Office for Law Enforcement Standards (OLES), we are conducting a thorough study to identify the determining factors for effective protection against the various types of bullets on the market.

Lyle E. Levine and Richard Rhorer (822)

The impact of a bullet on soft body armor is a remarkably complex process involving complex geometries (including the density and weave pattern of the body armor fibers) and high-strain-rate properties of the bullet and armor materials. Complicating the issue further, recent lead-free bullet designs are being produced with a wide range of materials (copper, tin, iron, tungsten, zinc and polymers) and processing conditions (sintering, cold-pressing and injection molding). The mechanical behavior of these new bullet designs can be dramatically different from those of the conventional lead bullets for which soft body armor has been designed. Degradation of body armor materials with age, mechanical wear and exposure conditions (moisture and light) is also important. A long-term, comprehensive project to address all of these issues was started this fiscal year.

Planned tasks for bullets include:

- High-strain-rate testing of bullets (longitudinal and diametral) and bullet materials using the NIST Kolsky bar facility. Approximately 600 tests will be required.
- Corresponding low-strain-rate testing using a conventional mechanical testing machine.
- Metallographic and chemical analyses of bullet materials.

Planned tasks for soft body armor materials include:

- Design and construction of a miniature Kolsky bar for high-strain-rate testing of fibers.
- Design and construction of tensile cages for miniature and existing Kolsky bars.
- Exposure of fiber test samples to degrading conditions (light, moisture and abrasion)
- High-strain rate testing of as-received and degraded individual fibers, multiple non-braided fibers, and braided fiber bundles. Approximately 2000 tests will be required.
- Corresponding low-strain-rate testing using a conventional mechanical testing machine.

These tasks will be complemented by finite element modeling of:

- High-strain-rate bullet tests using measured high-strain-rate behavior of bullet materials.
- Fiber and fiber bundle tests using measured high-strain-rate behavior of fiber materials.
- Bullet impacts with woven body armor fabric.

Figure 1: *Frangible 9 mm bullet and remains after impact.*

Expected Impacts

The test data will be used by the U.S. Department of Justice to determine what actions are required to ensure that soft body armor provides adequate protection to police officers in the field. The experimentally validated finite element models will be used to screen combinations of bullets and body armor designs to identify potential threats at an early stage.

Contributors and Collaborators

S. Banovic, R. Fields, L. Ma, S. Mates (Metallurgy Division, NIST); M. Kennedy, E. Whitenton (Manufacturing Metrology Division, NIST); T. Burns (Mathematical and Computational Sciences Division, NIST)

Marine Forensics and Preservation of Historic Shipwrecks

Historic shipwrecks are valuable cultural resources continuously under attack by their environment. Preservation techniques aimed at slowing corrosion processes and mechanically stabilizing shipwreck structures are being modeled and designed in coordination with the National Park Service, NOAA, and the U.S. Navy. These techniques are being applied to such wreck sites as the USS Arizona*, the* Ellis Island Ferry*,* RMS Titanic*,* CSS Hunley*, and the* USS Monitor.

Tim Foecke

Since the attack on Pearl Harbor on December 7th, 1941, the wreck of the *USS Arizona* has been slowly corroding and collapsing. The monument that straddles the wreck sees over 700,000 visitors per year, and there is immense interest in preserving the wreck for as long as possible. Aside from the historical interest, there are substantial environmental risks associated with any large-scale collapse of the wreck, as there is still an estimated 500,000 gallons of fuel oil trapped below water.

The Submerged Cultural Resources Unit (SCRU) of the National Park Service (NPS) has responsibility for maintaining and preserving the wreck. Based on our past experience in marine forensics, SCRU approached the Metallurgy Division for assistance in several areas.

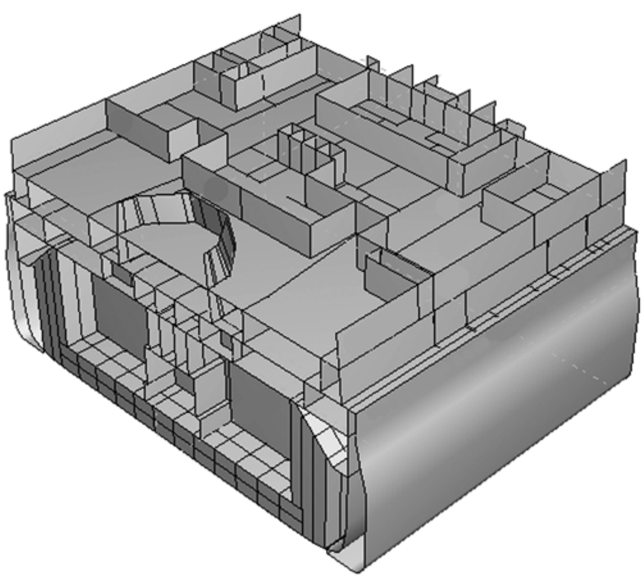

Figure 1: *Finite element model of the center section of the* USS Arizona*, where fuel oil is believed to be concentrated.*

Advice is being given on methods to measure the remaining thickness of the hull through the existing bioencrustation. A finite element model (Figure 1) is under construction, and techniques are being developed to map the corrosion current data gathered by the NPS over the last 20 years onto the model in the form of decreasing plate thicknesses.

The tools developed in this project will eventually be transferred to companies and organizations that are responsible for monitoring submerged wrecks containing hazardous materials, allowing them to better simulate critical conditions.

Figure 2: *Cross-section of a rivet extracted from the submarine* HL Hunley*, showing slag flow lines on the left. The submarine, the first to sink an enemy ship, is currently on shore in Charleston, SC).*

In addition to the *USS Arizona*, we are providing assistance and technical expertise to NPS, NOAA and the Navy regarding preservation of the Ellis Island Ferry, the *CSS Hunley* (Figure 2), the *USS Monitor* (partially salvaged), and the *RMS Titanic*. NIST participated in a multi-agency remote survey of the *Titanic* wreck in June 2004 at the University of Rhode Island, satellite linked to the NOAA Ship *Ron Brown*. Ongoing analysis of the photos and videos taken during this expedition will attempt to map the degradation of the wreck and chart the impact of any human visits.

Contributors and Collaborators

L. Ma, S. Banovic (Metallurgy Division, NIST); L. Murphy, M. Russell, D. Conlin (Submerged Cultural Resources Unit, National Park Service); Lt. J. Weirich (NOAA); Cdr. J. Morganthou (CINCPAC, U.S. Navy)

Kinetic Penetrators and Amorphous Metals

Environmental and political debate on the continued use of depleted uranium (DU) alloys has led to increased efforts at developing low-cost, reduced-toxicity replacement penetrator materials with similar ballistic performance. The Metallurgy Division has been working with the Army Research Laboratory (ARL) on a novel tungsten-amorphous metal composite material as one of these new DU alloy replacements. The project relies on the Metallurgy Division's expertise in rapid solidification processing and instrumented powder consolidation to provide these composite materials to the ARL for ballistic testing.

Stephen D. Ridder

Bulk amorphous metal (BAM) alloys are a relatively new class of alloys that solidify amorphously in castings with cross-sections as large as 10 mm across, a significant improvement over the sub-1 mm castings of conventional amorphous metal alloys. The Army's interest in high-density BAM alloys is a result of their need for a new armor-piercing projectile material to replace the current Depleted Uranium technology.

Modern, tank-fired armor-piercing munitions are high-velocity projectiles machined from DU alloys or from two-phase, tungsten-based heavy alloy (W–) composites. High-density materials are chosen to maximize the kinetic energy available for armor penetration. The projectile material is partially consumed by erosion or back extrusion as it enters armor plate. Current DU alloys are superior to available W-composites due to "continuous tip sharpening" compared to the tip blunting and "mushrooming" seen in the W-composites. This tip sharpening is generally attributed to adiabatic shear localization (ASL) and failure, a specific failure mode exhibited by DU alloys when rapidly loaded. Heat generated within the penetrator during high-strain-rate loading produces sufficient thermal softening of the DU alloy structure to overcome work-hardening in ASL bands concentrated near the tip of the penetrator that promotes rapid removal of deformed material. The continuously sharpened penetrator concentrates the remaining kinetic energy at the end of a relatively narrow tunnel, thus reducing energy loss and improving penetrator efficiency.

Recent work by the ARL has shown that BAM alloys have promise in providing the necessary ASL-like behavior that could lead to a W-composite penetrator material with performance similar to DU alloys.

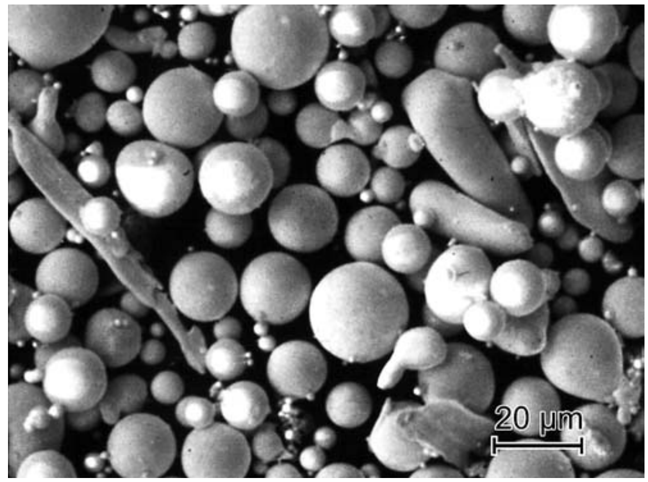

Figure 1: *Amorphous Hf alloy powder particles produced in NIST small-scale gas atomization facility.*

The Metallurgy Division designed and built a small-scale gas atomizer to study the composition-dependent solidification behavior of BAM alloys using small batch (250 g) processing to reduce material and processing costs. Figure 1 shows spherical amorphous Hf alloy powder particles recently produced. The material produced by this device is preferred to the more readily available comminuted melt-spun amorphous ribbon material because these spherical particles can be blended with tungsten powder and consolidated to produce a more homogeneous W-composite billet.

A hot isostatic press (HIP) has been instrumented with an eddy current sensor developed at NIST to follow the composite consolidation and provide the necessary quantitative, real-time monitoring of the progress of densification. This technology will allow full densification of the W-composite without inducing large-scale crystallization of the Hf based BAM powder.

Contributors and Collaborators

F.S. Biancaniello, C.E. Campbell, R.J. Fields, R.D. Jiggetts, U.R. Kattner, S.P. Mates (NIST), L. Kecskes (U.S. Army)

Ballistic Resistance of Polymeric Materials

Ballistic-resistant body armor has been credited with saving more than 2,500 lives, but new materials are constantly being developed, and there currently exists no method for evaluating armor over time to ensure the continued effectiveness of the protection. The objective of this project is to prevent catastrophic failure of personal body armor by developing a standard test method for reliability of the active polymeric materials that comprise them.

Chad R. Snyder and Gale A. Holmes

This research is focused primarily on two goals: (1) to link chemical structure and fiber mechanics to ballistic performance; and (2) to identify chemical mechanisms underlying reduction of ballistic performance, such as UV degradation and hydrolysis. Currently, one of the most promising models linking fiber mechanical properties to ultimate ballistic resistance is the work of Cunniff and Auerbach.[1] From a dimensional analysis study, these researchers concluded that the principal fiber property of interest in relating the ballistic performance of any armor system material to any penetrator, independent of system areal density, is the $(U^*)^{1/3}$ parameter, which is the product of fiber specific toughness and strain wave velocity and is expressed in m/s, *i.e.*,

$$(U^*)^{1/3} = \left[\frac{\sigma\varepsilon}{2\rho} \left(\frac{E}{\rho} \right)^{1/2} \right]^{1/3} \qquad (1)$$

where σ is the fiber ultimate axial tensile strength, ε is the fiber ultimate tensile strain, ρ is the fiber density, and E is the linear elastic fiber modulus. This model has recently been given a firmer theoretical framework by Phoenix and Portwal.[2]

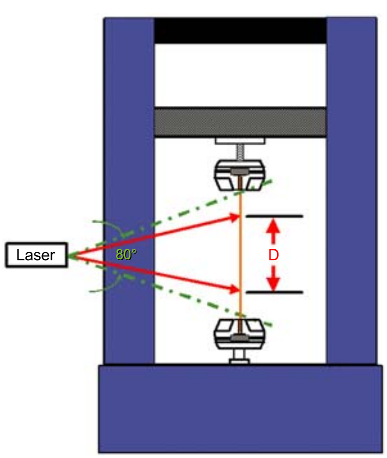

Figure 1: *Single fiber fragmentation testing instrument.*

Most tests of ballistic fiber strength are performed on yarns rather than single fibers. However, obtaining yarns from vests currently in service tends to be very invasive and decreases the strength of the vest. Obtaining single fibers is far less invasive and, therefore, provides a potential mechanism for monitoring vests while in service without comprising the integrity of the vests. Because of recent research in our laboratory into polymer composites, there are a number of instruments available to conduct tests on single fibers. One such instrument is an automated single fiber fragmentation testing machine (see Figure 1), which allows us to obtain stress, strain, and modulus. In the past, resin samples containing a single carbon or glass fiber were put into the machine. For this project, we have developed a method to characterize isolated fibers without a resin matrix.

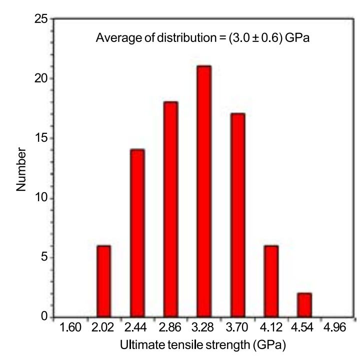

Figure 2: *Single fiber data obtained on single E-glass fibers.*

To verify the capability to measure isolated ballistic fibers, we have recently completed measurements on isolated glass fibers (Figure 2). The results are within the predicted limits, and testing is ongoing on single ballistic fibers. To address the influence of chemical structure on ballistic fiber performance and durability, model compounds are being prepared to identify any UV and/or hydrolytic degradation pathways of the fibers through mass, infrared, and nuclear magnetic resonance spectroscopies.

References

1. P.M. Cunniff and M.A. Auerback, *23rd Army Science Conference*, Assistant Secretary of the Army (Acquisition, Logistics and Technology), Orlando, FL (December 2002).
2. S.L. Phoenix and P.K. Porwal, *International Journal of Solids and Structures* **40**, 6723 (2003).

Contributors and Collaborators

B. Fanconi, K. Flynn, D. Liu, W. McDonough, D. VanderHart, W. Wallace (Polymers Division, NIST); K. Rice (Office of Law Enforcement Standards, NIST)