15. STRUCTURES

15.1 STRUCTURAL FAILURE INVESTIGATIONS

15.1.1 INTRODUCTION

Investigations of the causes of structural failures were a particularly important part of the CBT program from 1975 to 1990. Failure investigations are distinguished from disaster investigations, which also were important for CBT and BRFL and are described in the next section, by their focus on a particular structure and by the absence of an extreme loading. The importance of failure investigations has both technical and pubic policy dimensions. Technically, it is important to understand the physical causes of a failure, determine whether existing standards are adequate to prevent such failures or whether the standards require revision, and disseminate these findings to the profession to avoid repetitions of the failure. Public policy attention is characteristic for major failures as the press, political leaders, concerned groups such as construction labor unions, and the general public become concerned about the safety of the class of structure involved in the failure.

Failure investigations generally do not involve structural research, though they may show needs for research when loadings or mechanisms of failure are found to be inadequately understood. Why then should NBS/NIST do failure investigations? There is a substantial sub-discipline of forensic engineering and architectural firms available to conduct failure investigations for a fee. Congressional hearings [1] made it very clear why NBS/NIST should investigate technically or politically important structural failures. Private investigations generally were funded by a party involved in legal action related to the failure, and therefore viewed as biased. Also, the reports of private investigations generally are sealed by the court as part of the resolution of the case and become unavailable to those not directly involved in the case, but who wish to understand causes in order to avoid repetitions.

As a result of important, successful structural failure investigations conducted by CBT, in cooperation with the Department of Labor's Occupational Safety and Health Administration (OSHA), and at the request of local government authorities, NBS was given a legislative mandate for structural failure investigations in its authorization legislation for fiscal year 1986 [2].

> *The National Bureau of Standards, on its own initiative, but only after consultation with local authorities, may initiate and conduct investigations to determine the causes of structural failures in structures which are used or occupied by the general public.*

Even with this legislation, NBS/NIST lacked authority to demand access to a failure site and information about the structure. Thus for effective investigations of private buildings, local governmental authorities would need to use their regulatory powers to provide access for NBS to the site and data. For federal facilities, NBS/NIST would need the authorities of the responsible federal agency. For failures during construction that injure or kill workers, OSHA has the necessary authority for access and often engaged CBT to investigate on its behalf.

To implement its authorization for structural failures investigations, CBT worked with the National Conference of States for Building Codes and Standards (NCSBCS) to develop a model agreement for a local government and NBS to collaborate in an investigation [3]. However, in the period of this history, through 2000, this agreement was not used.

The building community, Congress and the general public were highly appreciative of the structural failure investigations conducted by CBT. This awareness of the quality and importance of CBT's work were significant in Congressional rejection of the Reagan Administration's proposals for each and every fiscal year from 1984 through 1990 to eliminate or cut in half CBT.

15.1.2 SKYLINE PLAZA APARTMENT TOWER AND PARKING GARAGE

The progressive collapse of this apartment building under construction was triggered by the failure of an upper story floor as a result of premature removal of formwork.

At 2:30 pm on Friday, March 2, 1973, a portion of the apartment tower collapsed for its full height while concreting was underway on its 24th floor and shoring removal was underway on its 22nd floor, and the impact of the debris caused a horizontal progressive collapse of the entire parking garage under construction adjacent to the tower [4]. Fourteen construction workers were killed, four in the garage and ten in the tower, and another 34 were injured.

Initiative is important in failure investigations. Upon learning of the accident from the news, staff of CBT's Structures Division went to the nearby site in the Division's van, gained access for initial reconnaissance, and made contact with OSHA's inspection team. On Monday, March 5, 1973, OSHA requested NBS to ascertain the cause of the collapse and to determine whether non-compliance with OSHA standards had contributed to the collapse. A rapid investigation was required since OSHA had only six months in which to file charges related to violations.

The tower was of reinforced concrete flat plate construction and planned for 26 stories. The parking garage planned for four levels was of unbonded, post tensioned flat plate concrete construction with construction underway for slab B-2, the second level from the top.

The investigation of the tower collapse included studies of the status and condition of the shoring, the properties of the concrete and reinforcing steel, and finite element analyses of the flexural and shearing stresses in the slab. It was determined that premature removal of shoring on the 22nd floor caused punching shear failure of the slab around one or more columns at the

23rd floor. The weight of the debris resulted in failures of the lower floors for the full height of the building. Numerous violations of OSHA standards had contributed to the collapse. E.V. Leyendecker and George Fattal produced a very complete report that became a model for subsequent failure investigations and stimulated study of the maturity (strength gain with time and temperature) of concrete and shoring practices to improve safety of concrete construction.

Understanding of the horizontal progressive collapse in the parking garage was more challenging. The nominal panel dimension was 9 m x 8 m (spacing between columns in the two principal directions) and the garage had a total plan area of 12 by 11 panels 104 m x 91 m. The falling debris impacted only two or so of the 132 panels, but all collapsed by shearing about the columns, which remained standing with the slabs pancaked at the column bases. Because of the importance of this failure, NBS funded a detailed, near full scale, laboratory investigation of the performance of the unbonded post tensioned slab and columns. However, the laboratory testing did not reproduce the failure observed in the field.

15.1.3 COOLING TOWER AT WILLOW ISLAND, WV

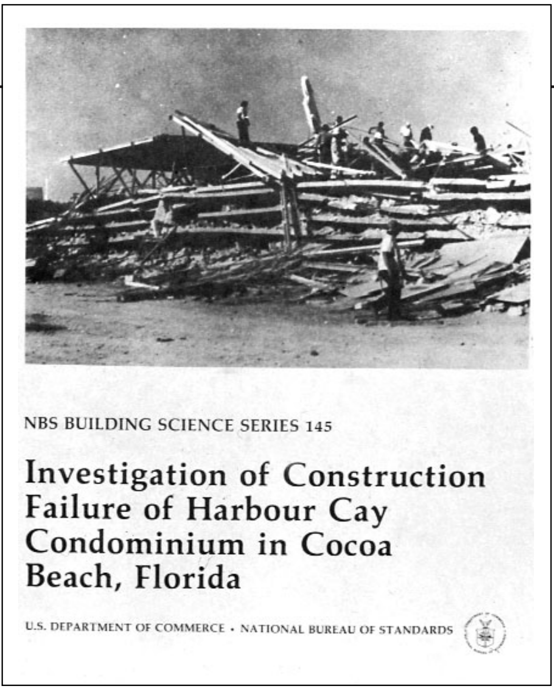
Shortly after 10 am on April 27, 1978, 51 workers were killed when the top portion of a reinforced concrete hyperbolic cooling tower, being constructed at the Pleasants power station, collapsed with the formwork and scaffolding it supported. CBT investigators arrived at the site on April 29, 1978, in response to a request by OSHA to assist in the investigation of the collapse and determine its most probable cause. CBT conducted field, laboratory and analytical studies [5] and had access to data from OSHA and the constructor.


Collapse of a portion of a reinforced concrete hyperbolic cooling tower.

The tower had reached a height of 61 m of its planned 131 m. Construction was underway on the 29th lift using scaffolding supported only by the concrete of the 28th lift which had been placed the previous day. Detailed studies were made of the patented construction system, site operations, properties of the concrete and other materials, components of the concrete hoisting and scaffolding system, loads acting at the time of collapse, and of the forces generated in the reinforced concrete shell in comparison to its strength. The conclusion was that the most probable cause of the collapse was imposition of the construction loads on the concrete of the 28th lift before it had gained sufficient strength to support these loads. This failure demonstrated dramatically the importance of measuring in-place concrete strengths before initiating a critical construction operation. H.S. Lew received the Bronze Medal Award of the Department of Commerce in 1980 for his leadership of the investigation, and the Silver Medal Award in 1982 for his development of construction safety guidelines to reduce risks of future failures due to immature concrete.

15.1.4 HARBOUR CAY CONDOMINIUM

The Harbour Cay Condominium, a five-story flat-plate reinforced concrete building under construction, collapsed shortly after 3 pm on March 27, 1981, killing 11 workers and injuring another 23. The collapse occurred during placement of the roof


NBS BUILDING SCIENCE SERIES 145

Investigation of Construction Failure of Harbour Cay Condominium in Cocoa Beach, Florida

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

Post disaster investigation report of Harbour Cay Condominium collapse.

slab. OSHA requested NBS assistance in investigation of the most probable cause of the collapse. The NBS investigators arrived on site on March 28, 1981, but were limited to general observations of the site until search and rescue operations, which substantially modified the debris, were completed.

The investigation [6] included review of contract drawings and specifications, observations of the site and debris, review of OSHA's interviews with witnesses to the collapse, tests of the strength of concrete and reinforcing steel, and analyses of the loads acting at the time of collapse, forces induced in the structure and the resistance of the structure. The most probable cause of collapse was a combination of design and construction errors: the design did not consider the possibility of punching shear failure and therefore specified a slab thickness of 203 mm when 277 mm was required; top reinforcing steel in the slab at the column was placed lower than specified further reducing the punching shear resistance.

While the slab thickness was less than the building code specified, the slab thickness and reinforcement placement specified in the structural drawings would have provided sufficient punching shear resistance to withstand the construction loads. A careful analysis of the reinforcement shop drawings by George Fattal and Nicholas Carino revealed that incorrect bar support chairs were used in critical portions of the slab.

15.1.5 KANSAS CITY HYATT REGENCY WALKWAYS COLLAPSE

On Friday July 17, 1981, at 7:05 pm two suspended walkways within the atrium area of the Hyatt Regency Hotel in Kansas City, MO collapsed during a dance. One hundred thirteen people died and 186 were injured. In terms of loss of life and injuries, this was the most devastating structural collapse to have taken place in the United States. On Monday July 20, 1981, Senator Thomas Eagleton on Missouri contacted Ernest Ambler, director of NBS, to request that technical assistance be provided to Kansas City. Ambler agreed, and later in the day Kansas City Mayor Richard Berkley requested technical assistance. Two NBS structural research engineers, Edward Pfrang and Richard Marshall, visited Kansas City on July 21 and met with the Mayor and other City officials. On July 22, Mayor Berkley formally requested that NBS independently ascertain the probable cause of the collapse of the walkways.

However, access to the site and data relevant to the failure were not easily attained. Kansas City provided access to its regulatory data, but did not use its authority to provide access to private data. Edward Pfrang, chief of CBT's Structures Division, worked forcefully and skillfully with the press, attorneys for plaintiffs and defendants, and the courts to obtain access to the site, the remnants of the skywalks and debris, and construction documentation. However, access never was gained to structural calculations and change orders involving the skywalk structural system.

The skywalks that fell had crossed the atrium at the fourth and second floor levels [7]. The fourth floor skywalk was suspended by hanger rods connecting the skywalk's crossbeams to the trusses supporting the atrium roof. The second floor skywalk was immediately beneath the fourth floor skywalk and suspended by hanger rods connected to the crossbeams in the fourth floor skywalk. Evidence from observers and debris revealed that the bolts and washers transferring the loads of the second and fourth floor skywalks to the hanger rods had deformed the fourth floor crossbeams and pulled through the crossbeams allowing the fourth floor skywalk to fall with its sus-

Collapsed walkways in the Hyatt Regency Hotel atrium.

pended second floor skywalk to the atrium floor below.

CBT, with support from the NBS Center for Materials Science, inspected the atrium area and the debris stored in a warehouse, weighed debris to ascertain the weights of the walkways, removed selected materials for laboratory testing, reviewed documents from design and construction, videos made just before and after the collapse, and photographs from the accident site. Laboratory studies were conducted of mockups to represent conditions at the time of failure, and of actual specimens from the debris. Analytical studies determined the response of the skywalks to the loads at the time of collapse.

The investigation revealed that the original design for connection of the crossbeams to the hanger rods, which had the hanger rods running continuously through the fourth floor crossbeams to the second floor crossbeams, was not in accord with applicable codes and standards and had only 53 percent of the required capacity. The design had been changed to suspend the second floor skywalk from the fourth floor skywalk, rather than on continuous hanger rods, resulting in a doubling of the forces that had to be transferred from the fourth floor crossbeams to the hanger rods. This doubling of the force on an already inadequate connection was the cause of the collapse.

The investigation received much public attention and CBT's work was highly commended (sidebar). CBT staff, notably Richard Marshall and E.V. Leyendecker, worked very effectively under intense scrutiny by the press and attorneys. Matt Heyman, chief of NBS's Public Information Division, was very helpful in dealing with the press and guiding CBT's staff in their interactions.

Editorial from the Kansas City Times on February 27, 1982

On July 18, 1981, no one in this area was prepared mentally or technically to investigate the causes or causes of Kansas City's worst disaster. Two days later, Sen. Thomas F. Eagleton, followed by Mayor Richard L. Berkly, Sen. John C. Danforth and Rep. Richard Bolling, called on the National Bureau of Standards in Gaithersburg, Md., to investigate the collapse of the Hyatt Regency sky walks.

For those politicians it was second nature to turn to the unique resources of the federal government for a thorough and impartial study that no party involved - not the city, the hotel owner, the builder or anyone else - could have provided. The mandate of the NBS is "to strengthen and advance the nation's science and technology and to facilitate their effective application for the public benefit." The NBS is singularly suited to investigate such complex disasters as the Hyatt.

In the Hyatt investigation, the client is the public of the entire country, the people who use buildings in the course of their lives. The NBS study is paid for with taxpayers' money and the results are matters of public record, for all interested parties to see and learn from.

Ultimately, the results of the study could revolutionize building design and inspection procedures. Such a move would start from a broader base of public acceptance because of the impartial manner in which the NBS team worked to meet its primary obligation to satisfy the public's right to know what happened and why.

Imagine how different the results of the Hyatt study might have been had no pool of experts existed at the NBS headquarters. Imagine where the public would be had there been no such specialized federal agency for this confused, bewildered city to turn to in its time of great need.

The building community was greatly interested in the investigation for both the physical causes of the failure and for the failures in the building process that had allowed the severe deficiencies in design and construction to have escaped attention. Edward Pfrang's effectiveness in the investigation and dissemination of its results was a significant factor in his being offered and accepting the position of Executive Director of the American Society of Civil Engineers (ASCE) in 1983. In 1982, he and Richard Marshall received the Gold Medal of the U.S. Department of Commerce for their leadership of the investigation. The building community's concern to improve its processes to avoid such defects and accidents in the future led to ASCE's development of a Manual of Professional Practice [8].

15.1.6 RILEY ROAD INTERCHANGE RAMP, EAST CHICAGO, INDIANA

On April 15, 1982, thirteen workers were killed and fifteen injured in the collapse of a highway ramp under construction in East Chicago, Indiana. OSHA requested technical assistance from NBS to determine the cause of the failure. CBT structural engineers arrived on the site on April 17. The investigation [9] included site investigation, experimental and analytical studies.

Collapse of a concrete highway ramp under construction.

The ramp was being built by the method known as cast-in-place, prestressed, post-tensioned concrete. At the time of the collapse, the ramp was unable to support its own weight and was supported by a temporary support system know as "falsework." The conclusion was that cracking of a concrete pad supporting a falsework tower was the triggering mechanism of the collapse. Deficiencies contributing to the collapse were: omission of wedges between falsework stringers and crossbeams, inadequate strength of the concrete pads, lack of stabilization of falsework towers against longitudinal movement, and poor weld quality in U-heads supporting cross beams at the top of the falsework towers. This investigation highlighted the importance of careful consideration of the design of all components of the temporary support system used in concrete construction.

15.1.7 STRUCTURAL ASSESSMENT OF THE NEW U.S. EMBASSY OFFICE BUILDING IN MOSCOW

On September 24, 1986, CBT director Richard Wright was called by staff of the Senate Appropriations Committee. "Could you assess the structural integrity of the new U.S. Embassy Office Building in Moscow?" The answer was "yes." "Could you do it in six months for $500,000?" The answer was "we do not yet know enough about the situation to make an estimate." Anyhow, a few days later The Continuing Appropriations Act for Fiscal Year 1987, Public Law 99-591, directed the NBS to conduct an independent assessment of the new U.S. Embassy Office Building in Moscow, in six months and for $500,000. The assessment was to include "an assessment of the current structure and recommendations and cost estimates for correcting any structural flaws and construction defects." Though no structural failure occurred, this study is included here because of its similarity to a failure investigation in both the technical work and the high visibility and priority given the investigation [10].

Under terms of a 1972 agreement between the U.S. and the Soviet Union, the Soviets were responsible for the detailed design and construction of the Embassy Office Building with a Soviet building system widely used in Moscow. This system is comprised mostly of precast reinforced concrete structural elements. The general design was prepared by U.S. firms from 1973 to 1976, construction at the site began in 1979, structural framing was in place in June 1982, exterior walls were substantially complete in November 1983, but construction was suspended in August 1985, except for placement of a temporary roof in November 1986. Construction was suspended because of concern for electronic security in the building (but NBS investigators were instructed to observe nothing related to electronic security). However, official U.S. inspections of the building had observed apparent structural defects so NBS was instructed to provide "an assessment of the current structure and recommendations and cost estimates for correcting any structural flaws and construction defects."

Access to the site and data were difficult to attain. The U.S. and Soviet Union were in a process of expelling each other's diplomats, Soviet workers had been withdrawn from the Embassy making it difficult to support NBS investigators on the site, the U.S. State Department was restricting official visitors to Moscow, and the Soviet Union was not eager to permit entries. NBS management realized the importance of the assignment and assigned Samuel Kramer, deputy director of the National Engineering Laboratory, widely acquainted with Congress and federal agencies, and an inspired expediter, to arrange for access to data on the building available in the U.S. and for access to supplies in Moscow. Kramer skillfully used the Congressional priority to obtain the permissions and resources needed for success of the investigation.

Security and logistical restrictions limited the number of CBT staff who could visit the site and have full access to data on the building. Nicholas Carino was the leader of the project, and William Stone, whose rock climbing expertise provided important access to the structure, also was fully involved in the investigation. Mary Sansalone provided detailed review of the structural plans and calculations and prepared summaries for use at the site. Alexander Rosenbaum, an émigré well informed on Soviet design and construction practices, was engaged to assist in studying the calculations, plans and characteristics of the building system. Because management involvement was needed in the project and site work, Richard Wright participated with technical emphasis on structural steel aspects, and James Gross, deputy director of CBT, participated with technical emphasis on masonry aspects.

With a tight deadline and a Moscow winter approaching, it was frustrating to be unable to visit the site until December 17-19, 1986, but there was much useful work to be done in studying the calculations, plans and information available in the U.S. Fortunately, the building was heated. The initial visit provided an overview of the condition of the structure and building. This information provided insights for planning the investigations during the second site visit from February 17 to March 6, 1987, and for laboratory studies of typical details prior to the second site visit. Carino, Stone and the rest of the project team put in long hours in the field and laboratory to meet the project deadline with a well-received report.

CBT investigator Nicholas Carino, research structural engineer, uses a borescope to examine the condition of the joint between segments of precast columns in the U.S. Embassy Office Building in Moscow. The investigation revealed many cases where large voids were present in the joints between precast structural members.

The investigation found that structural materials and components used in the building were of generally good quality, but important deficiencies existed that should be corrected before the building would be occupied. It had been hard to find a properly grouted connection between pre-cast concrete columns, or a properly completed connection between pre-cast concrete shear wall panels and adjacent panels or columns. All such connections required inspection and completion. The design had not considered resistance to progressive collapse; recommendations were made for enhancing this resistance. The costs for the remedial measures were estimated to be less than $2 million and to take less than a year to accomplish, if the work were done in the Washington, DC area.

Some critics felt that progressive collapse should not be an issue, but subsequent U.S. experience with terrorist attacks has shown its importance. The building has been modified for electronic security, repaired and placed in service. Nicholas Carino received the Silver Medal Award of the Department of Commerce in 1987 for his leadership of the investigation.

15.1.8 L'AMBIANCE PLAZA BUILDING COLLAPSE

The L'Ambiance Plaza apartment building under construction in Bridgeport, Connecticut collapsed at about 1:30 pm on April 23, 1987, killing 28 construction workers. The building was being constructed by the lift slab method. Two-way reinforced and post-tensioned concrete slabs for floors and roof were cast on the ground, and then lifted by jacks on the steel columns to their final positions. At the time of the collapse, three levels of parking garage slabs and six levels of floor slabs were in place in the east tower, three levels of parking garage slabs and three levels of floor slabs were in place in the west tower, and a package of three slabs was being placed in a temporary position in the west tower. In the collapse, all of the slabs fell.

Appearance of the L'Ambiance Plaza apartment building that collapsed during construction.

OSHA requested technical assistance from NBS in determining the most probable cause of the failure on April 24, 1987; CBT engineers led by Charles Culver, chief of the Structures Division, arrived on site at 6:00 pm that same day. While priority was given to rescue efforts, CBT collected data on the nature of the failure of various structural elements. In its investigation [11], CBT used: information on the construction procedures and collapse from interviews of survivors and witnesses conducted by OSHA; project documentation including design specifications, plans, shop drawings, construction records, testing laboratory reports, and project correspondence; laboratory tests of samples removed from the collapsed structure; data from a subsurface investigation of the site after the collapse; and analytical studies of the stability of the columns and forces induced in the slabs and connections during the lifting operations.

The most probable cause was determined to be excessive deformation of a shearhead that connected the jacking rods to the package of three slabs, which led to the slipping off of a jacking rod, which increased loads on adjacent jacking rods causing them to slip off or fracture, which led to failure of the slabs, whose debris caused lower slabs to also fall, which led to general collapse of the west tower, which led to collapse of the adjacent east tower, probably as a result of impacts of debris or pulling action from the west tower. The mechanism of shearhead deformation and slipping off of the jacking rod was reproduced in the laboratory within the range of loadings used in the lifting operations.

Much controversy arose about the cause of this failure. A number of papers were published in the American Society of Civil Engineers' Journal of Performance of Constructed Facilities (12) and alternative hypotheses discussed [13]. OSHA showed its confidence in the investigation by engaging Culver to become director of its Office of Construction and Engineering in 1988. However, this did become the final CBT construction failure investigation for OSHA because, under Culver's leadership, OSHA subsequently conducted its own investigations. As a result of the failure and the lessons learned in its investigations, the American Society of Civil Engineers established a Task Committee on Lift Slab Construction to develop guidelines for successful lift slab construction and OSHA published new rules on this construction method.

15.1.9 ASHLAND OIL STORAGE TANK COLLAPSE

On January 2, 1988, a 15.6 million liter capacity oil storage tank at the Ashland Petroleum Company Floreffe Terminal near West Elizabeth, Pennsylvania collapsed as it was being filled to capacity for the first time since it was reconstructed at the site after more than 40 years of service in Cleveland Ohio. The contents flowed into the Monongahela River approximately 40 km upstream from Pittsburgh and contaminated the water supplies of many communities on the Monongahela and Ohio rivers. Congressman Doug Walgren, the Fire Marshall of Allegheny County and the Governor of Pennsylvania requested NBS to conduct an independent technical investigation into the cause of the collapse. The Ashland Petroleum Company provided full access to the site and its data on the tank and its use to NBS's and others' investigations.

Brittle fracture propagation occurring in tank caused it to rupture and spill its full contents into the neighboring Monongahela River.

Data were obtained from NBS field observations, laboratory and analytical studies [14], from the investigation of the Pennsylvania Tank Collapse Task Force appointed by the Governor, and from the Battelle Columbus Division investigation sponsored by Ashland. The cause of the failure was determined to be brittle fracture initiating from a flaw existing prior to the reconstruction of the tank. Complete rupture of the tank occurred because its steel was of inadequate toughness at the operating temperature to prevent brittle fracture propagation. The steel did not meet the standards of the American Petroleum Institute which were effective at the time of reconstruction of the tank. Concern was expressed for the risk that other tanks might be in service with steels of inadequate fracture toughness for their conditions of use.

John Gross of CBT led the investigation for NBS and John Smith of the Institute for Materials Science and Engineering led its metallurgical aspects.

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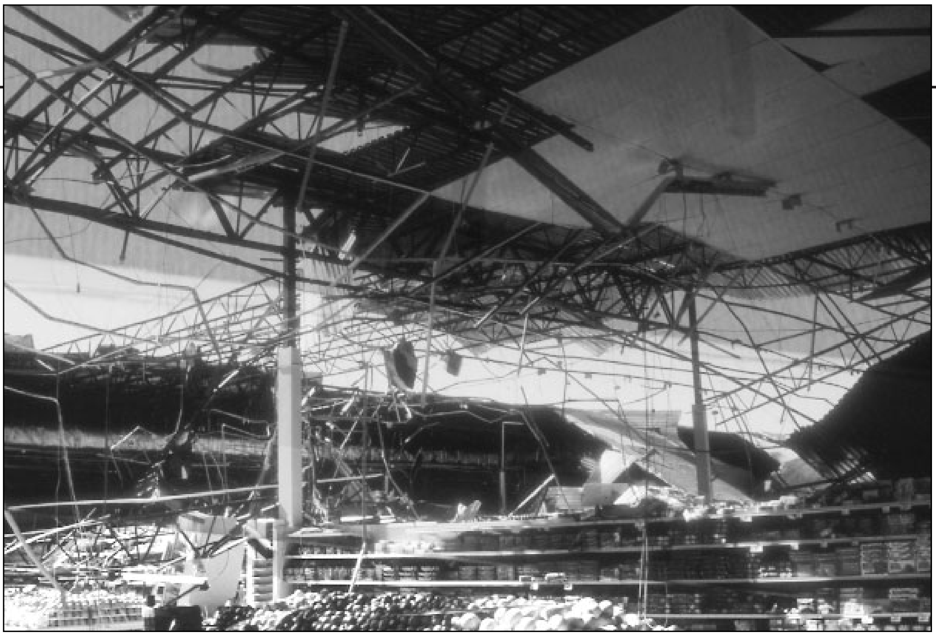
15.2 DISASTER INVESTIGATIONS

15.2.1 INTRODUCTION

Post disaster investigations were important to BFRL and its predecessor organizations for both technical and public policy reasons. Technically, an extreme wind, earthquake or conflagration would test the performance of structures and fire protection systems at a scale impossible in the laboratory. Investigations allow confirmation of engineering knowledge and practice or identification of unanticipated mechanisms of failure and needs for research. Politically, a disaster would focus public and policy makers attention on the importance of good structural performance to gain impetus for implementation of improved practices, such as up to date wind or seismic design and construction practices, or for research and development of improved practices when the best available were shown not to prevent unacceptable losses. Thus, disaster investigations have been the impetus for sustained program funding, such as the National Earthquake Hazards Reduction Program, for significant one-time funding to respond to needs for improvements of practice revealed by the disaster, and for public policies such as executive orders for implementation of seismic design and construction practices.

The disaster investigations cited here did not include research or in-depth technical studies needed to develop technical bases for improvements in practice. Rather, they cited evidence of the harmful consequences of not using up-to-date wind or seismic design and construction practices, and identified opportunities to learn from the performance of structures in the extreme environment. They did lead to much research, by CBR/BFRL and others, to address issues identified in the investigations. From the 1989 Loma Prieta and the 1994 Northridge earthquakes substantial supplemental appropriations from Congress were received to address the research needs identified.

Post disaster investigations by NBS began in 1969 with the investigation of Hurricane Camille and continued with investigation of tornado damage in Lubbock, Texas in 1970, the San Fernando Earthquake in 1971, and the flooding from Hurricane Agnes in 1972. These are covered in earlier histories of building research at NBS. Under the leadership of Edward Pfrang for the San Fernando Earthquake, NBS showed the advantages in private and public policy attention of being the first to publish a substantive report. However, subsequent managers and staff were unwilling to devote the necessary energy and resources, and break commitments to other deadlines, to maintain this advantage.



Structural damages to low-rise commercial and residential constructions caused by the 1997 Jarrel, Texas tornado included the partial collapse of the roof of a supermarket. The roof was supported by open-web steel trusses.

15.2.2 WIND INVESTIGATIONS

Richard Marshall joined NBS in 1968 and devoted his career, until retirement in 1996, to field and laboratory studies of wind forces and effects on structures. He led many important wind disaster investigations. Following the December 25, 1974 Cyclone Tracy in Darwin, Australia, he collaborated with Australian authorities in investigation of the loads on damages to buildings [1]. Findings for residential buildings were very applicable to U.S. practice: wall sheathing must be strong and well attached to function in transmittal of lateral forces, and roofs must be firmly connected to walls and walls to foundations in order to hold structures together. Although about 80 percent of the city's houses were severely damaged by winds estimated to range from 49 m/s to 76 m/s (3 s gust at 10 m above ground) well constructed buildings were observed to have performed well. Sound design and construction can minimize damages.

Marshall participated in the National Academies' investigation of the effects of Hurricane Hugo in 1989 on Puerto Rico, the Virgin Islands and Charleston, SC [2, 3]. Hugo was the costliest hurricane to date to impact the United States. Marshall's investigation focused on the Virgin Islands and Puerto Rico and on estimation of the wind forces from limited meteorological measurements and from assessments of damages based on the qualities of construction. It showed that wind velocities in Puerto Rico were less than specified in the building code. Properly designed and constructed buildings indeed showed minimal damages. Wind velocities in the Virgin Islands exceeded code levels, but the code levels were grossly inadequate for the wind hazard and should be increased.

Hurricane Andrew struck south Florida on August 24, 1992, to cause an estimated $25 billion in damage. Marshall was co-leader of a joint investigation by the Wind Engineering Research Council (WERC) and NIST. Walter Rossiter of NIST also participated in the studies of damages to roofing. The investigation concluded that wind speeds, related to engineering design conditions, were between 49 m/s and 56 m/s , while the current engineering standards and codes called for between 51 m/s and 53 m/s. These findings led to disagreements with the National Oceanic and Atmospheric Administration (NOAA) authorities who estimated peak wind velocities of 89 m/s. Actually, both were correct. The engineering design wind was the velocity averaged over the time required for a particle to travel 1.6 km, about 30 seconds, and measured at a height of 10 m above the ground. The NOAA figure was for a short duration gust in a very localized "microburst" area of high intensity wind. Most of the damages and losses were due to structures not being built in accord with the existing building codes. NIST's review requirements did not allow Marshall and Rossiter to be authors of the WERC report, but Marshall did conduct follow-up studies for the Department of Housing and Urban Development (HUD) to recommend improved wind resistant standards for manufactured ("mobile") homes [4]. After much controversy, these standards were adopted in HUD's mandatory standard for manufactured homes and have substantially reduced wind vulnerability at modest cost.

Tornado wind velocities also tend to be estimated at very high levels by the National Weather Service giving the impression that extensive damages are inevitable "acts of God." Indeed wind velocities at the edge of the funnel can be very high and impractical to resist in small buildings, but funnels are narrow and velocities drop off rapidly beyond the funnel so that well constructed small buildings can survive something less than a direct hit. Long Phan and Emil Simiu investigated damages in the Jarrell, Texas tornado of May 27, 1997 [5] to assess the wind speeds and Fujita (F) Class of the tornado. The area had no building code and the destroyed buildings had connections of roofs to walls and walls to foundations that would not meet an appropriate building code. The damages were consistent with an F3 tornado with speeds ranging from 71 m/s to 92 m/s rather than the F5 of 117 m/s to 142 m/s tornado identified by the National Weather Service.

On May 30, 1998, at 8:38pm (CDT), a violent tornado struck the town of Spencer, South Dakota, a small farm community approximately 72 km west of Sioux Falls, leaving 6 dead, more than 150 injured, and nearly 90 percent of a total 195 structures in the six-by-seven blocks community destroyed. Following the passage of this tornado, BFRL researchers visited Spencer and conducted aerial and ground surveys to document structural damage. Post disaster investigations provide valuable information on the responses of structures to extreme loads. Complete documentation of instances of successful or poor performance can yield valuable lessons that can be used to improve construction practices. The picture shows the complete collapse of a water tower in Spencer.


Collapsed steel water tower in Spencer, South Dakota due to the May 30, 1998 Spencer tornado.

15.2.3 EARTHQUAKE INVESTIGATIONS

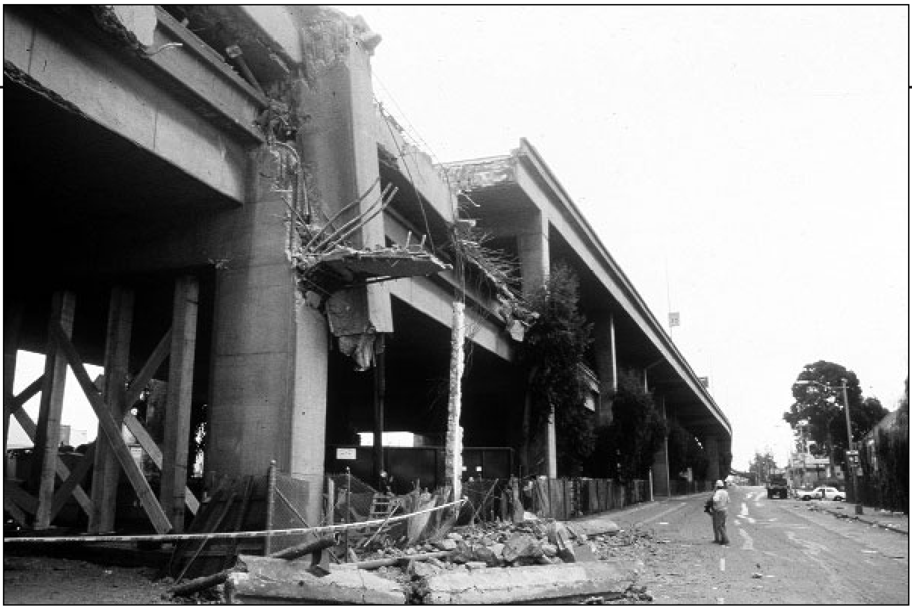
The Miyagi-ken-oki, Japan, Earthquake of June 12, 1978, was of great interest to the U.S. because the earthquake was large, Richter magnitude 7.4, provided design level shaking to many modern structures including an operating nuclear power reactor, and was well instrumented to allow good comparison of structural performance to the actual ground shaking. Because of CBT's leadership in the creation and operation of the U.S-Japan Panel on Wind and Seismic Effects, a multi-disciplinary, multi-agency, U.S. team received access and Japanese government support in investigating the earthquake [6]. Structural performance was generally good, for instance the nuclear reactor was similar to U.S. designs and was undamaged. Damages were concentrated where deep, soft soil conditions amplified motions, suggesting that design criteria consider these effects, where structural asymmetry concentrated distortions, or where bridge piers were non-ductile.

The Mexico earthquake of September 19, 1985, was of great interest to the U.S. because severe damages occurred to modern buildings located at a large distance of 386 km from a great earthquake of Richter magnitude 8.1. Such conditions could occur in the United States: for Chicago from a repeat of the great 1811-12 New Madrid, MO earthquakes, for California cities in response to a great earthquake on the San Andreas fault, or for the Pacific Northwest from a great earthquake in the subduction zone off shore. Therefore, the CBT-led Interagency Committee on Seismic Safety in Construction (ICSSC) organized a multi-agency, multii-disciplinary team to investigate the earthquake [7]. The investigation showed that amplifications of motion in areas of deep, soft soil deposits were responsible for the most severe damages. Standards and codes for the U.S. needed updating to account for such foundation conditions. William Stone received the

Bronze Medal Award of the Department of Commerce in 1987 for his leadership of the investigation.

The magnitude 7.1 Loma Prieta, California earthquake of October 17, 1989, which caused extensive damages in the San Francisco Bay area at a distance of 96 km from the epicenter, showed the relevance of the Mexico City experience. Again, damages were concentrated in areas of deep, soft soil deposits as shown by the investigation of the CBT-led ICSSC [8] and others. Severe damages occurred to bridge structures and loss of water supplies exposed San Francisco to the threat of conflagration like that of 1906. Fortunately, winds were light and the fires did not spread. Congress and the Administration proved much more sensitive to U.S. experience than to warnings from foreign earthquakes and provided substantial supplemental funding to study seismological aspects and building performance to develop recommendations for improvements of standards for new and existing structures. The President also issued an Executive Order, which had been drafted years before by the ICSSC, to call for application of up-to-date seismic standards in the design and construction of federal and federally leased, assisted or regulated new building construction.

H.S. Lew led the investigations of the Loma Prieta earthquake and the subsequent Northridge and Kobe earthquakes. In addition to his good sense for structural behavior he showed remarkable capabilities to elicit the cooperation of emergency management authorities, team members, other investigators and the representatives of the organizations responsible for the facilities being studied.



A failure of supporting columns resulted in the collapse of the bi-level I-880 Viaduct during the 1989 Loma Prieta Earthquake in the San Francisco area.

The magnitude 6.8 Northridge, California earthquake of January 17, 1994, caused severe damages. The investigation of the BFRL-led ICSSC [9] and others showed that most damages occurred to structures already known to be inadequate. However, there was a big surprise in the brittle behavior of modern welded steel frame buildings, and a demonstrated need to improve standards for deformation compatibility of structural members. Major supplemental funding was provided for studies of design criteria for new welded steel frames and for retrofit criteria for existing welded steel frames, and for improvement of the performance of new and existing bridges. (BFRL's work on welded steel frames is described in section 15.12.) Again the risk of conflagration following an earthquake was demonstrated; a BFRL-led workshop [10] developed recommendations for research and improvement of practices. The President issued another ICSSC-developed Executive Order to assess the seismic risks produced by existing hazardous federal or federally leased buildings.

The magnitude 6.9 Kobe, Japan earthquake of January 17, 1995 took 6,000 lives and caused economic losses estimated at over $200 billion. Because the earthquake was exemplary of what a close in earthquake could do to a modern city, the BFRL-led U.S. side of the U.S.-Japan Panel on Wind and Seismic Effects conducted an investigation of the performance of structures, lifelines and fire protection systems in the earthquake [11]. The findings and recommendations of the study identified research and improvements in practice to reduce urban earthquake disasters, and are being addressed in ongoing U.S. and Japanese earthquake risk reduction programs.

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15.3 STRUCTURAL RELIABILITY

Structural codes and standards provide the foundation of good engineering practice and a framework for addressing safety and serviceability issues in structural design. They identify natural and man-made forces that must be considered, define magnitudes of these forces for design, and prescribe methods for determining structural resistance to these forces. The framers of these documents on which the structural engineer places so much reliance must address the question: "How safe is safe enough?" on behalf of society as a whole. Code development is a grave responsibility and, for the most part, has been done well since failures of constructed facilities are rare. On the other hand, such failures, when they do occur, are highly visible and their consequences are severe in human and economic terms for all involved.

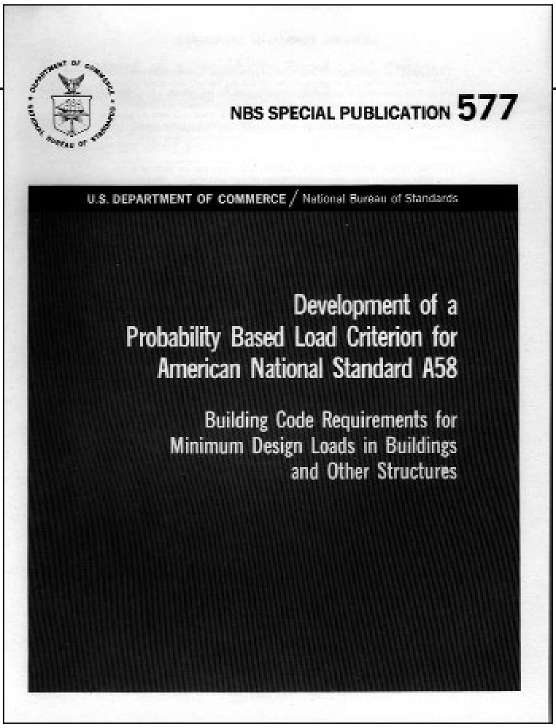
At the root of the structural safety problem is the uncertain nature of the man-made and environmental forces that act on structures, of material strengths, and of structural analysis procedures that, even in this computer age, are no more than models of reality. The natural consequence of uncertainty is risk. Structural engineering, as applied to civil construction and in contrast to other engineering fields, relies heavily on analysis and computation rather than on testing because of the scale and uniqueness of typical civil projects in both public and private sectors. Structural codes are linked to computational methods of safety assessment, and their primary purpose is to manage risk and maintain safety of buildings, bridges and other facilities at socially acceptable levels.

Until the 1960s, the safety criteria in structural codes were based on allowable stress principles. The structural system being designed was analyzed under the assumption that it behaved elastically (the fact that structures seldom behave elastically to failure was disregarded). Uncertainties were addressed by requiring that the computed stresses did not exceed a limiting stress (at yielding, rupture, instability) divided by a factor of safety. These factors of safety were selected subjectively; one might, for example, identify the load acting on a structure and then design the structure so that the elastic stresses due to that load remain below 60 percent of the stress at yield (implying a factor of safety of 5/3). Of course, no one knew what the risk of failure was for such a structure. The factor of safety of 5/3 simply represented a value judgment on the part of the standard-writers, based on past experience. During the past century, with the advent of formal structural calculations, the trend in the factor of safety generally has been downward.

This judgmental approach to safety works well as long as the technology being dealt with is stable or evolves slowly and there is opportunity to learn from experience in the standard development process. Occasionally, of course, engineers become overconfident, ignorance catches up or construction practice overreaches the state of the art, and failures occur. More than in most other engineering disciplines, the profession of structural engineering seems to have progressed by learning from its mistakes. To the discomfort of many structural engineers, this learning process usually takes place in the public arena.

The late 1960s also witnessed the beginnings of the move toward a new philosophy toward structural design in the United States, Canada and Western Europe. The shortcomings of allowable stress design were recognized in many quarters, and a search was underway for more rational approaches to distinguish between conditions (termed limit states) directly related to acceptable structural performance, to ensure safety under rare but high-hazard conditions, and to maintain function under day-to-day conditions. Concurrently, the new field of structural reliability was developing around the notion that many of the uncertainties in loads and strengths could be modeled probabilistically. Advances were being made in first-order reliability analysis, stochastic load modeling and supporting statistical databases. Several probabilistic code formats were suggested, including an early version of Load and Resistance Factor Design (LRFD) for steel buildings. However, these early proposals were relatively narrow in scope, and dealt with single construction technologies in isolation from one another. With this lack of coordination, there was a risk that as different standard-writing groups moved toward probability-based limit states design, each would develop load requirements independently, and that these load requirements would be mutually incompatible in structural engineering practice, where construction technologies usually are mixed. Leaders of the profession agreed that structural load requirements must be independent of construction technology to facilitate design with different construction materials.

At this time, the Secretariat for American National Standard Committee A58 on Minimum Design Loads for Buildings and Other Structures was administered in the Structures Division of the Center for Building Technology. The antecedents at NBS for this standard dated back to 1924, when the Building and Materials Division published a report under the auspices of the Department of Commerce Building Code Committee on Minimum Live Loads. Research on probabilistic methods in structural standards and codes was a central thrust in the CBT throughout the 1970s, with the work of Charles Culver and Bruce Ellingwood in probabilistic analysis of live and fire loads [1,2], of E.V. Leyendecker and Ellingwood on provisions for general structural integrity to reduce risks of progressive collapse [3], of Ellingwood on wind and snow loads [4] and load combinations for reinforced concrete design [5], and of Emil Simiu, Richard Marshall, James Filliben and in wind loads [6]. This work stood at the intersection of research and practice; its products were internationally recognized in both research and professional communities and incorporated in the A58 standard.



NBS SPECIAL PUBLICATION 577

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Development of a
Probability Based Load Criterion for
American National Standard A58

Building Code Requirements for
Minimum Design Loads in Buildings
and Other Structures

NBS SP 577 joint authored by Bruce Ellingwood, research structural engineer, CBT on probability based load criterion for A58[7].

Various standard-writing groups in the United States agreed that the A58 Standard was the logical place for material-independent load criteria to appear. In 1978, Ellingwood accepted the challenge of leading the development of a set of common probability-based load requirements for limit states design that would be compatible with all common construction technologies. He arranged for three other leaders in reliability-based structural codes, Professors Theodore Galambos, James MacGregor, and C. Allin Cornell (father of NIST's 2001 Nobel Prize winner, Eric Cornell), to join him at NBS during the summer of 1979 to develop a set of load requirements using advanced structural reliability analysis methods and statistical databases. The objectives of this joint effort were to:

- recommend a set of load factors and load combinations for inclusion in the A58 Standard that would be appropriate for all types of building construction (e.g., structural steel, reinforced and prestressed concrete, engineered wood, masonry, cold-formed steel and aluminum), and
- provide a methodology for various material specification groups to select resistance criteria consistent with the A58 load requirements and their own specific performance objectives.

The product of this collaboration was, Development of a Probability-based Load Criterion for American National Standard A58, NBS Special Publication 577 [7], which was published in June, 1980. Subsequent developmental work on probability-based codes in the United States in such diverse applications as buildings, bridges, offshore structures, navigation facilities, and nuclear power plants in the intervening two decades all can be traced back to this one seminal document.

The probability-based load criteria in NBS Special Publication 577 were first implemented through the voluntary consensus process in the 1982 edition of American National Standard A58. They have appeared in all editions of that Standard (the standard has been published as American Society of Civil Engineers (ASCE) Standard 7 since 1985) since then, most recently ASCE Standard 7-98, and have remained essentially unchanged since 1982.They have been adopted by reference in all standards and specifications for limit states design in the United States, including the American Institute of Steel Construction's LRFD Specification for Steel Structures (1986, 1994 and 2000 editions), ASCE Standard 16-95 on LRFD for Engineered Wood Construction, and American Concrete Institute Standard 318-96 (Appendix B). They also have been adopted in the International Building Code 2000, the new single model code in the United States. In retrospect, the move toward probability-based limit states design may seem like a small step, but in fact it was not. It required a thorough re-examination of the philosophical and technical underpinnings of the current bases for structural design, as well as the development of supporting statistical databases. Much of this supporting research is still utilized in code development and improvement activities worldwide. It has become the basis for structural design as it is now practiced by professional engineers in the United States.

It is unlikely that these probability-based load criteria efforts would have been completed and implemented in professional practice successfully had they been managed by any other than CBT/NBS. CBT was viewed as representing the structural engineering community at large rather than any one special interest group. The load criteria were completed successfully because they were developed by engineering researchers who were familiar, first of all, with the structural engineering issues involved, as well as with the reliability tools necessary for analyzing uncertainty and safety.

In a more general sense, the load criteria that were developed in this study and reported in NBS Special Publication 577 have had a profound influence on structural codes used worldwide in design of buildings and other structures. The approach taken - developing supporting statistical databases, calibrating to existing practice, and calculating load and resistance factors to achieve desired reliability levels - was followed in a subsequent National Cooperative Highway Research Program study to develop limit states design procedures for highway bridges, now published as an American Association of State Highway and Transportation Officials standard. The National Building Code of Canada will adopt a similar approach to combining loads in its 2000 edition.

Standard development organizations in other countries, including Australia, New Zealand, South Africa, Japan, and Western Europe (through the Eurocodes) have adopted similar load combination requirements for structural design. The NBS Special Publication 577 load combinations have been recognized internationally as the first developed using modern probability-based load combination analysis techniques. They have stood the test of time, and only minor changes have been required as a result of additional research and advances in other areas of structural load modeling during the past two decades.

The probabilistic approach to structural safety embodied in this groundbreaking activity continues to resonate in the structural engineering community. The aftermath of natural and man-made disasters during the past two decades, rapid evolution of design and construction methods, introduction of new technologies, and heightened expectations on the part of the public, all have made judgmental approaches to ensuring safety of the built environment increasingly difficult to defend. The traditional practice of setting safety factors and revising codes solely based on experience does not work in this environment, where such trial and error approaches to managing uncertainty and safety may have unacceptable consequences. In an era in which standards for public safety are set in an increasingly public forum, more systematic and quantitative approaches to engineering for public safety are essential. The probabilistic approach addresses this need, and in the past two decades has been widely accepted worldwide as a new paradigm, for design of new structures and evaluation of existing facilities. NBS Special Publication 577 was the pathbreaking study in this area.

A number of archival publications were prepared from the NBS study. Most notably, references 8 and 9 were awarded the American Society of Civil Engineers' Norman Medal in 1983. The Norman Medal is the oldest and most prestigious of ASCE's prizes, and is awarded annually to the paper(s) that the ASCE Awards Committee and the Board of Directors judge most significant and meritorious for the advancement of the civil engineering profession. Also, in 1980, Ellingwood received the Silver Medal of the Department of Commerce for his work on common load factors for structural design. For an application of the approach to the punching shear resistance of lightweight concrete structures exposed to ice loadings, Long Phan received the Department of Commerce Bronze Medal Award in 1990.

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15.4 The Maturity Method

On March 2, 1973, portions of a multi-story apparent building, under construction in Fairfax County, Va., suffered a progressive collapse (see section 15.1.2 above and [1]). The Occupational Safety and Health Administration requested the assistance of NBS in determining the technical cause of the collapse. The report prepared by the CBT investigators concluded that the most probable cause of the failure was premature removal of formwork that resulted in stresses exceeding the capacity of the relatively young concrete [1].

CBT researchers recognized the need for a simple field method to estimate in-place concrete strength to allow critical construction operations to be done safely. In 1975, H. S. Lew of the Building Safety Section and Thomas Reichard of the Structures Section embarked on a study of a relatively new approach known as the maturity method. The maturity method relies on the measured temperature history of the concrete to estimate strength development during the curing period. The temperature history is used to calculate a quantity called the maturity index. For each concrete mixture, the relationship between strength and the maturity index is established beforehand. The strength relationship and the measured in-place maturity index are used to estimate the in-place strength. The method originated in England in the early 1950s, but was not used in U.S. practice.

The initial CBT research confirmed that the maturity method could be used to represent the development of concrete strength (and other mechanical properties) under different curing temperatures [2,3]. One of the publications [3] reported on a rigorous analysis of the relationships between the water-cement ratio of the concrete and the parameters in a proposed equation for the strength-maturity relationship. In 1980, the American Concrete Institute recognized the significance of the CBT research and awarded Lew and Reichard the prestigious Wason Medal for Materials Research.

In the early CBT work, the initial concrete temperature was the same for all specimens, and the specimens were moved into different constant-temperature chambers after molding. In a subsequent study, Lew and Charles Volz, a student at The University of Texas at Austin, examined the applicability of the maturity method under simulated field conditions [4]. In this case, specimens were stored outdoors and companion specimens were placed in a standard curing chamber. The objective was to determine whether the strength-maturity relationships for the field-cured specimens were the same as those for the companion laboratory-cured specimens. The results revealed that this was not the case. In the CBT research, a traditional equation was used to compute the maturity index from the temperature history.

On April 27, 1978, there was a major construction failure of a cooling tower being constructed in Willow Island, WV. OSHA again requested NBS to assist in determining the technical cause of the failure (see section 15.1.3 above). The CBT investigators concluded that the most likely cause of the collapse was insufficient concrete strength to support the applied construction loads [5]. This failure convinced CBT researchers of the urgent need for standards on estimating in-place concrete strength during construction. Thus the Structures Division began an in-depth study of the maturity method and other applicable methods. The objective of the work on the maturity method was to gain an understanding of the cause of the discrepancies in the earlier work [5]. Nicholas J. Carino, a new member of the Structures Division staff, led this work. He approached the problem from a point of view more theoretical than that of the previous work. By making use of new data analysis tools, Carino established a deeper understanding of the maturity method and explained the cause of the previous discrepancies [6-9]. In 1983, NBS recognized his contributions and awarded Carino the Bronze Medal of the Department of Commerce. In 1984, armed with this new understanding, Carino proposed a draft standard practice on the use of the maturity method. In 1987, ASTM Practice C 1074 was adopted [10].

In 1986, Rajesh C. Tank, a PhD student at Polytechnic University (Brooklyn, N.Y.), joined NBS as a guest worker and collaborated with Carino on further developing the maturity method. The work resulted in two publications [11,12]. One of these [12] reported on the temperature dependence of strength development of different concrete mixtures. The American Concrete Institute recognized the significance of their work and awarded Tank and Carino the 1994 Wason Medal for Materials Research.

In 1991, Carino published a book chapter [13] that provided a comprehensive review of the maturity method. This chapter is regarded as the "bible" for any new student of the maturity method. The latest BFRL research effort was published in 1992 [14], and it demonstrated that the method could be applied to mixtures with low water-cement ratios, which are typical of high-performance concrete.

In the late 1990s, the Federal Highway Administration publicized the maturity method, along with other technologies for testing concrete, to state highway departments throughout the U.S. As a result, in 2000 many state highway departments were adopting ASTM C 1074 into their standard specifications. Widespread use of in-place test methods, such as the maturity method, will result in safer and more economical concrete construction.

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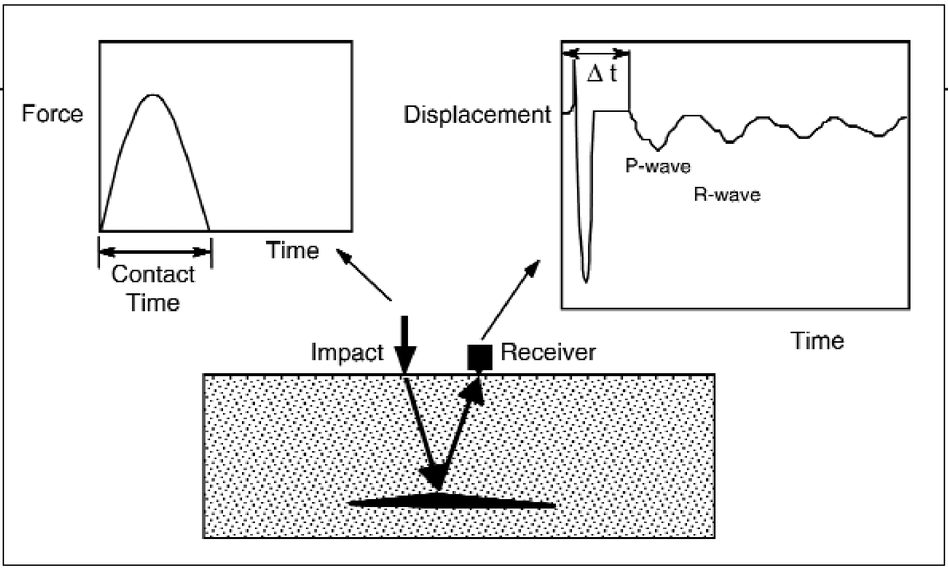


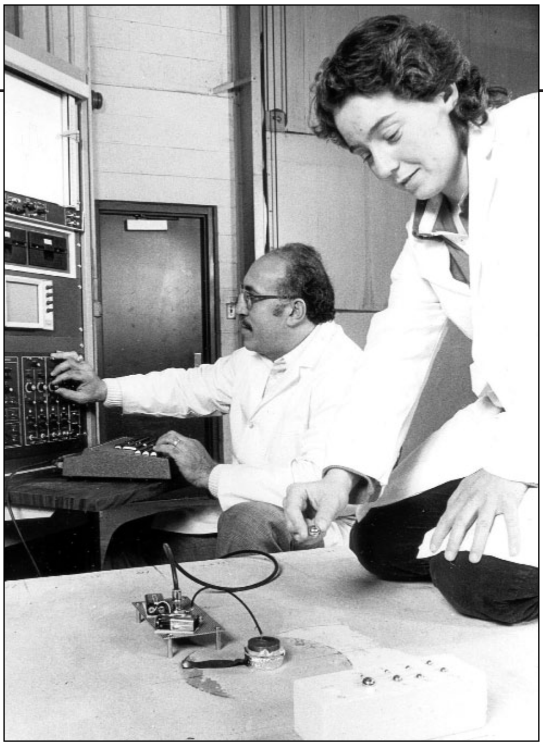
The impact-echo method: mechanical impact is used to generate stress waves and a receiver next to the impact point measures the resulting surface motion. Analysis of the measured surface motion permits detection of subsurface defect.

15.5 THE IMPACT-ECHO METHOD

In 1983, the focus of CBT research on in-place testing of concrete shifted toward the detection of internal defects. Despite the advances in non-destructive testing of metals, there was no simple reliable method for locating flaws in concrete. Based on a review of available techniques, it was decided to pursue a test method based on stress waves because their propagation in a solid is affected directly by mechanical properties [1]. The technique that was developed became known as the impact-echo method [2], and its principle is illustrated in the figure below. Mechanical impact on the surface is used to generate a high-energy stress pulse that travels into the concrete. The pulse is reflected by an internal defect and travels back toward the surface where a receiver close to the impact point monitors its arrival. The pulse continues to undergo multiple reflections between the defect and the surface. Thus a resonant condition is created and the frequency of arrival of the pulse is determined. Knowing the stress wave speed in the concrete, the measured frequency can be used to calculate the flaw depth.

This research effort was highly successful due to a combination of factors. First, the research team was composed of individuals with different capabilities and backgrounds. Nicholas J. Carino, the team leader from the Structures Division, provided expertise in concrete technology and test methods; Mary Sansalone, a PhD student from Cornell University, provided expertise in finite element modeling; and Nelson N. Hsu, of the Manufacturing Engineering Laboratory (MEL), provided expertise in wave propagation. Second, the availability of numerical modeling tools permitted the researchers to simulate stress wave propagation under different test conditions. The numerical simulations established the scientific basis for the impact-echo method and permitted the development of optimum testing configurations. Third, a new point-displacement transducer, which was developed by Thomas Proctor of MEL as a reference for calibrating acoustic emission transducers, turned out to be ideal for impact-echo testing. Fourth, the researchers took advantage of developments in signal processing and used frequency analysis of the recorded signals. Finally, the basic capabilities of the method were established by a combination of numerical studies and companion controlled-flaw studies.

The initial success was the result of using Proctor's point transducer in combination with steel balls to produce the required short duration impacts. The American Concrete Institute (ACI) recognized quickly the significance of the new approach underlying the CBT research. In 1986, Carino was awarded the ACI Wason Medal for Materials Research for a paper that reviewed the fundamentals of wave propagation in concrete and summarized the first series of controlled-flaw studies [3]. The next significant development was the use of the fast Fourier transform technique to convert the recorded time domain waveforms [4] into the frequency domain [5]. This development simplified signal interpretation. Next, extensive simulations of different test conditions were carried out by using a state-of-the-art stress-wave propagation code developed at the Lawrence Livermore National Laboratory. In 1987, Sansalone and Carino received the CBT Communicator Award for a series of papers that summarized the results of these simulations [6-9]. At the same time, Stephen Pessiki, a graduate student from Cornell University, demonstrated the feasibility of using



Nicholas J. Carino, research structural engineer, and Mary Sansalone, graduate student, are shown performing some of the initial tests that led to the development of the impact-echo. Sansalone is about to create an impact by dropping a steel ball next to the point displacement transducer and Carino is ready to observe the resulting surface motion displayed on a waveform analyzer.

the impact-echo method to monitor setting and early-age strength development of concrete [10].

Another key aspect of the CBT research was a series of laboratory controlled-flaw studies that verified the results of the numerical simulations and demonstrated the breadth of applicability of the impact-echo method [11-14]. One of the studies dealt with the detection of delaminations in concrete slabs, such as bridge decks, that result from corrosion of the reinforcement. In 1991, the American Concrete Institute awarded Sansalone and Carino the Wason Medal for Materials Research for their paper on the delamination study [11].

At the conclusion of the CBT effort in the late 1980s, Sansalone continued the research at Cornell University. Advances resulting from the Cornell work included developing a PC-based field test system, extending the application to more complex structures, and establishing a technology transfer program to train new users. Eventually, Sansalone published a book to document, in one place, the theory and capabilities of the impact-echo method [15].

In 1996, Carino and Sansalone collaborated on the development of a draft standard on the use of the impact-echo method to measure the thickness of plate-like concrete structures. Carino championed the draft standard through the ASTM standardization process, and in 1998, Test Method C 1383 was approved [16].

The CBT research leading to the impact-echo method is an excellent example of how a multi-disciplinary team can solve a difficult problem. The combination of theory, simulation, and experimental verification provided a solid foundation for what is being recognized worldwide as a powerful tool for "seeing" into concrete.

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15.6 WIND ENGINEERING

Since the late 1960s to the 1990s wind engineering technology has been advanced by NIST through theoretical, experimental, and computational research.

15.6.1 ENGINEERING MICROMETEOROLOGY

NIST has initiated the use in wind engineering of consistent descriptions of the atmospheric boundary layer, based on first fluid dynamics principles and state-of-the-art meteorological research. Those descriptions pertain to: the mean wind speed profile in the surface layer and the dependence of the surface layer height upon wind speed and terrain roughness; the dependence on elevation of the spectrum of the longitudinal turbulent wind speed fluctuations, which affects tall building design; the shape of the spectrum for the very low frequencies of interest in deep-water offshore platform applications; and the dependence of the mean wind profile upon the centripetal accelerations inherent in cyclostrophic flows modeling hurricane winds [1].

15.6.2 EXTREME WIND CLIMATOLOGY

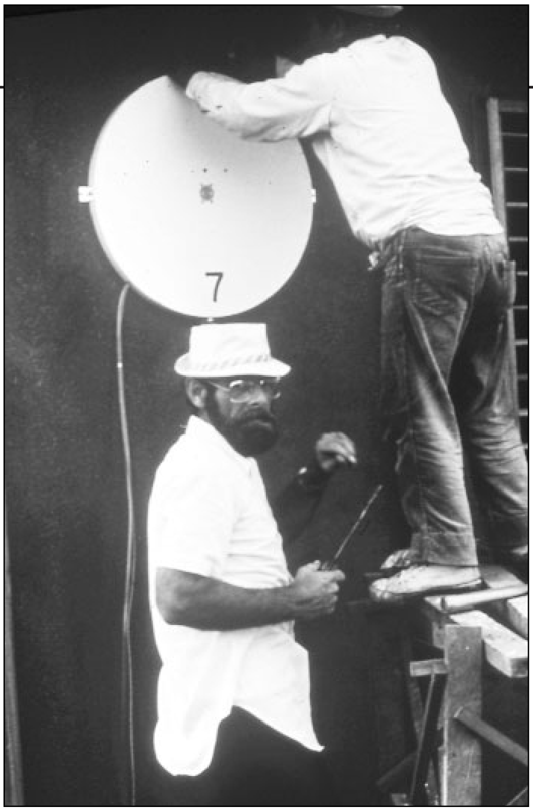
The reliability of structures subjected to strong wind loads depends upon the ratio between the design wind speeds specified in standards - usually wind speeds with a 50 year mean recurrence interval - and the extreme wind speeds causing structural damage or failure. This ratio depends upon the length of the upper tail of the extreme wind distribution. Using advanced statistical techniques, NIST (a) showed that extreme wind speed distributions used in the ANSI A58-1972 Standard were unrealistic, and (b) helped to introduce an improved distributional model in subsequent versions of the standard [2]. Following the development in the 1970s of novel approaches to extreme value estimation, NIST showed that, at most locations, extreme wind speeds have finite, rather than infinite upper tails. This finding allowed the development of structural reliability models resulting for the first time in realistic estimates of safety margins and failure probabilities for structures subjected to strong winds.

15.6.3 BLUFF BODY AERODYNAMICS AND WIND TUNNEL TESTING CRITERIA DEVELOPMENT

NIST has developed full-scale measurement techniques and obtained full-scale wind pressure measurements used all over the world for the calibration of wind tunnel measurements and the development of standard provisions on wind pressures [3, 4]. NIST has also contributed to the development of performance criteria for wind tunnels simulating the turbulent atmospheric boundary layers.

15.6.4 WIND LOADS ON LOW-RISE BUILDINGS

During 1973-1976, under an Agency for International Development contract, NIST developed information on design pressure coefficients for low-rise buildings used to improve the



Richard D. Marshall, research structural engineer, with Philippine Weather Bureau technician installing a pressure transducer to one of the wind test houses at the Quezon City, Philippines field test site.

A58.1 Standard (now ASCE 7). Richard D. Marshall served as principal investigator and Noel Raufaste as program coordinator. The research findings resulted in improvements to basic design data concerning the effects of extreme winds on low-rise, low-cost housing and other public service buildings in developing countries. It developed improved design criteria for building details. And it developed and demonstrated a methodology to assist suburban and rural building design for local wind climate. A variety of reports were published on this project [5]. Among the products of this project noteworthy was the film High Wind Study [6] that was awarded 2nd place in the 1976 Rome Film Festival for documentaries.

Raufaste and Marshall created an advisory committee of Philippine officials from 15 public and private sector organizations who collaborated with NBS to improve the wind-resistance of low-rise structures. They donated four test buildings at three field sites. The Philippine Weather Bureau and the University of Philippines were two key contributors. In addition, representatives from two of the four geographic wind prone areas contributed to this work. Jamilur Choudhury of the Bangladesh University of Engineering and Technology represented the Bay of Bengal countries and Alfrico Adams, a private civil engineering practitioner, heavily involved in codes and standards of the Caribbean, represented the Caribbean Countries. They contributed to the research and transferred findings to their respective parts of the world. The other two wind prone geographic areas: Southeast Asia and the US east and gulf coasts were represented by the Philippines and the US through the NBS study.

15.6.5 STRUCTURAL DYNAMICS

NIST developed linear models of the resonant and non-resonant effects of wind loading on high-rise structures that account for the imperfect spatial correlation of the wind pressures and their stochastic variability in time. Because wind speed fluctuations have large energies at frequencies close to the fundamental frequencies of vibration of compliant deep-water offshore platforms, it was widely believed for such platforms resonant effects due to the wind loading are prohibitively large. NIST developed a time-domain analysis used in conjunction with nonlinear hydrodynamic damping models, which showed that resonant amplification effects due to wind loading are in fact relatively small [7]. NIST's approach was adopted for use by the American Petroleum Institute.

15.6.6 STRUCTURAL RELIABILITY AND POST-DISASTER INVESTIGATIONS

Owing primarily to inadequate extreme wind modeling, early reliability models yielded the unrealistic result that the estimated failure probability of structures subjected to wind loads is one if not two orders of magnitude lower under wind than under gravity loads. NIST's later results on extreme wind distribution tails made it possible to show that this is not the case and to develop realistic estimates of wind load factors and of probabilities of failure due to wind loads [8]. NIST has also shown that standard wind loading provisions for the design of structures in hurricane-prone regions were inadequate, and led the effort to improve standard provisions accordingly. Structural reliability and performance models have been scrutinized by using observations of damage obtained during numerous, highly effective post-disaster investigations.

15.6.7 GLASS BEHAVIOR UNDER FLUCTUATING WIND LOADS

Using state-of-the art fracture models in conjunction with nonlinear analyses of stresses induced by fluctuating wind loads on glass panels, as well as innovative approaches to experimental glass strength characterization [9], NIST research was influential in the development of new standard provisions for glass panels subjected to wind loads.

15.6.8 DEVELOPMENT OF CRITERIA ON TORNADO WIND SPEEDS AND TORNADO-BORNE MISSILES SPEEDS

NIST developed criteria on tornado-borne missile speeds adopted by the Nuclear Regulatory Commission for the design of nuclear power plants [10]. NIST also initiated on-going research to modify the Fujita tornado intensity scale so observations of tornado-induced damage can lead to more realistic estimates of tornado speeds than had been previously the case.

15.6.9 DEVELOPMENT OF PERFORMANCE CRITERIA ASSURING HIGHER SAFETY LEVELS AND LOWER COSTS FOR STRUCTURES SUBJECTED TO WIND LOADING

Conventional standard provisions are based on wind loading simplified representations designed to accommodate slide-rule or pocket calculator capabilities. NIST has developed an IT-based methodology for the direct and practical use in design of unadulterated wind tunnel records of fluctuating wind pressures measured simultaneously at hundreds of points on the building surface [11]. By helping to eliminate material where it is superfluous and add it where it is needed, this methodology makes possible risk-consistent designs resulting in safer structures at lower costs. NIST also used this methodology in conjunction with time-domain nonlinear approaches to obtain for the first time in the history of structural engineering realistic ultimate capacities of structures subjected to fluctuating wind loads.

15.6.10 EDUCATION AND PRACTICE

Simiu and Professor Robert Scanlan have synthesized wind engineering knowledge and practice for use in graduate education and by practicing engineers in a world-recognized book [12].

15.6.11 AWARDS

In addition to the awards noted above for individual papers and activities, the National Society of Professional Engineers named Emil Simiu Federal Engineer of the year 1984 for his contributions to knowledge and practice in wind engineering. In 1999, the American Society of Civil Engineers named Richard Marshall the first recipient of the Walter J. Moore, Jr. Award for excellence in and dedication to the development of structural engineering codes and standards. In 2001, the Americas Conference on Wind Engineering created the Outstanding Wind Engineering Ph.D. Award in memory of Richard Marshall.

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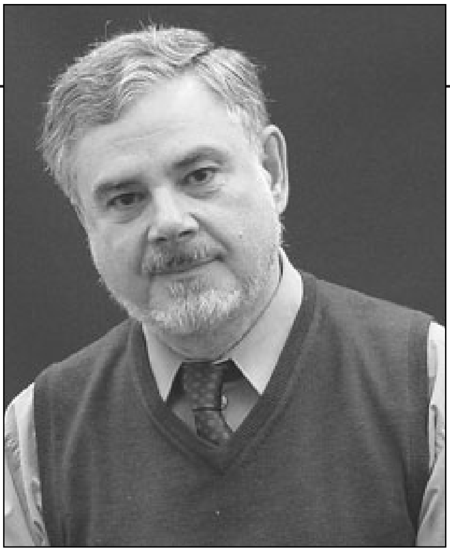
15.7 CHAOTIC DYNAMICS

Chaotic dynamics research at BFRL benefited at various stages from NIST work on the behavior of nonlinear electronics and mechanical engineering systems. It was motivated primarily by structural engineering and hydroelasticity modeling problems related to the design of deep water compliant offshore platforms.

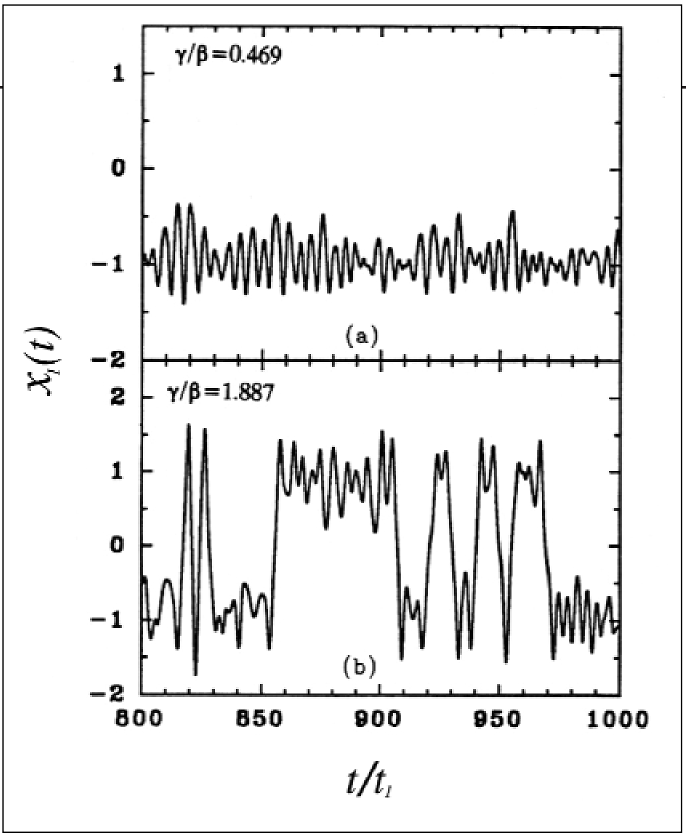
R. L. Kautz of the Electronics and Electrical Engineering Laboratory (Boulder) performed a series of studies of the dynamics of the Josephson junction, a multistable system that can exhibit chaotic behavior. The studies were supported mathematically and computationally by H. Fowler of the Information Technology Laboratory (ITL), who also helped BFRL chaotic dynamics research efforts. M. A. Davies and C. J. Evans of the Center for Manufacturing Engineering, with T. J. Burns of ITL, studied the dynamics of chip formation in machining hard metals, and D. G. Sterling of ITL/Boulder studied the hitherto unknown phenomenon of the synchronization of the motions of chaotic systems. BFRL benefited from interactions with most of these authors.



Emil Simiu, leader in wind research and chaotic structural dynamics.

In particular, Emil Simiu and G. R. Cook of BFRL and T. J. Burns of ITL collaborated within the framework of a NIST competence building project on computational and mathematical aspects of the chaotic behavior of a deterministic model of a galloping oscillator [1]. The competence project subsequently focused on the effect of stochastic excitation on the behavior of systems whose deterministic counterparts can exhibit chaotic behavior.

Experimental work on hydroelastic systems, conducted by BFRL at the David Taylor Research Center showed that stochastic excitation of multistable systems can promote dynamics indistinguishable in practice from chaotic behavior. Theoretical research by BFRL with M. R. Frey of the Statistical Engineering Division, ITL, confirmed the validity of this finding for a wide class of physically realizable multistable stochastic systems whose deterministic counterparts possess a Melnikov function [2]. The research made use of classical approximations of stochastic processes by finite periodic or quasiperiodic sums of harmonic terms with random parameters, which allow the application of the Melnikov approach -- originally devised for periodically or quasiperiodically excited systems -- to physically realizable systems with stochastic excitation. This work led to the development of a unified Melnikov-based approach to the study



(a) Non-chaotic and (b) chaotic time histories induced in a bistable dynamical system by dichotomous noise excitation.

of the dynamics of both deterministic and stochastic dynamical systems, and the conclusion that deterministic and stochastic excitations play similar roles in the promotion of chaos.

To the Melnikov function defined for the deterministic systems there corresponds in their stochastic counterparts a Melnikov process. Melnikov processes were subsequently used in studies of the chaotic behavior of systems with additive Gaussian noise, non-Gaussian infinitely-tailed noise, state-dependent (parametric) noise, and dichotomous noise.

The spectral density of the Melnikov process was shown to be equal to the spectral density of the excitation times the square of a system-specific transfer function. This relation can be used to assess the effect of the noise color upon the propensity of the system to experience jumps over its potential barrier(s).

With Office of Naval Research support, the stochastic Melnikov approach was used in a wide variety of applications, including: the generation by turbulent wind of along-shore currents in ocean flow over a corrugated bottom, open-loop control, buckled column snap-through, stochastic resonance, acceptable cut-off frequencies for experimentally generated colored noise excitation, and the chaotic behavior of auditory nerve fiber dynamics [3, 4, 5, 6, 7].

The BFRL research provided basic material for what is believed to be the first monograph in the literature on the study of transitions in stochastic systems from a chaotic dynamics point of view [8]. The monograph is designed for use by engineering, physics, and life sciences researchers whose primary interest is in applications. It covers the basic requisite material on the chaotic and stochastic dynamics of a wide class of nonlinear planar multistable systems, and provides detailed examples of applications in naval architecture, oceanography, structural/mechanical engineering, control theory, physics, and neurophysiology.

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15.8 THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

The National Earthquake Hazards Reduction Program (NEHRP) was authorized by the Earthquake Hazards Reduction Act of 1977, Public Law 95-124, to "reduce the risks of life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program." Its implementation plan was issued by the Executive Office of the President on June 22, 1978. CBT and BFRL have played significant roles in the development and accomplishments of NEHRP. NEHRP has been an extraordinary, and often exemplary, collaboration between federal agencies, state and local governments and the private sector.

15.8.1 BACKGROUND

CBT's predecessor, the Division of Building Research, began work in earthquake hazard reduction with its organization in 1969 of the U.S./Japan Panel on Wind and Seismic Effects under the U.S./Japan Program on Natural Resources, and its investigation of the performance of structures in the 1971 San Fernando, California earthquake. Both of these activities were led by Edward Pfrang. Later in 1971, Richard Wright and Samuel Kramer represented NBS in the Disaster Preparedness study of the Office of Emergency Preparedness (OEP) of the Executive Office of the President [1]. They worked with Ugo Morelli of OEP, Charles Thiel of NSF and Arthur Zeizel of HUD on needs for collaborative efforts to research, develop and implement building practices for disaster mitigation.

Charles Thiel was able to exploit the flexibility of the Research Applied to National Needs (RANN) program of NSF to fund private sector and university participants through NBS to prepare improved seismic design and construction provisions. NSF and NBS proceeded to convene and fund a national workshop to define a cooperative program on Building Practices for Disaster Mitigation (OEP was being eliminated as President Nixon streamlined his Executive Office and HUD was unable to provide co-sponsorship). The Structural Engineers Association of California organized the Applied Technology Council (ATC) to provide a mechanism to conduct studies for the improvement of building practices; its first such study was an input to the workshop on procedures and criteria for earthquake resistant design. The workshop [2] evaluated current practices, defined opportunities to improve practices based on documented research findings, recommended professional and public policy actions for implementation of improved practices and identified gaps in knowledge requiring further research.

Seismic design and construction provisions for buildings needed to use consistent loadings and resistance expressions for all types of buildings and all building materials to achieve consistent levels of safety. Since national standards were and are generally materials specific, a comprehensive program, involving all professional and materials interests, was needed to achieve nationally applicable provisions for all types of buildings and building materials.

NSF and NBS continued in 1973 to sponsor a study by ATC of a two-level seismic design approach based in principle on that used for the seismic design of nuclear facilities: a damage threshold spectrum representing earthquake motions having a moderate probability (50 percent) of being exceeded during the design life (70 years) of the structure, and a collapse threshold spectrum having a low probability (10 percent) of being exceeded during the design life. An engineering panel developed design provisions adapted from the 1973 Uniform Building Code, and each of eleven buildings was redesigned according to the design provisions by the one of ten firms that originally designed it. The study [3] found the approach workable but challenging for designers to grasp.

In 1974, NSF and NBS funded ATC to present the current state of knowledge in the fields of engineering seismology and engineering practice for seismic design and construction of buildings. ATC convened 85 recognized experts led by Roland Sharpe, project director, who had extensive experience in seismic design and in development of seismic design provisions, and Nathan Newmark, chairman of the project steering group, who was head of Civil Engineering at the University of Illinois and a leader in earthquake engineering research. Charles Culver of CBT oversaw the project for NBS. The provisions were intended to enable new and existing buildings to:

1. Resist minor earthquakes without damage,
2. Resist moderate earthquakes without significant structural damage, but with some non-structural damage,
3. Resist major or severe earthquakes without failure of the structural framework of the building or its component members and equipment, and to maintain life safety.

The resulting provisions [4] were a significant advance on existing provisions and were not recommended for adoption in building codes until a detailed evaluation was made of their workability, practicability and potential economic impact. Charles Culver received the Silver Medal of the Department of Commerce in 1977 for his leadership of the project.

15.8.2 ESTABLISHMENT OF NEHRP

Congressman George Brown and Senator Alan Cranston, both of California, led the Congressional efforts to produce the Earthquake Hazard Reduction Act of 1977. Karl Steinbrugge, an insurance industry expert in seismic damages, led a working group in the Executive Office of the President to develop the National Earthquake Hazards Reduction Program (NEHRP) in response to the Act. Charles Thiel represented NSF and Charles Culver represented NBS on the working group. The memorandum of transmittal and program document [5] are somewhat incoherent reflecting the conflict between the working group's desire for an effective program and the Administration's concern for controlling costs.

In the NEHRP, NBS was assigned:

- Development of seismic design and construction standards for consideration and subsequent adoption in Federal construction, and encouragement for the adoption of improved seismic provisions in State and local building codes.
- Assist and cooperate with the Department of Housing and Urban Development, other federal agencies (particularly those involved in research), National Institute of Building Sciences, professional organizations, model code groups, and State and local building departments, in continuing the development, testing, and improvement of model seismic design and construction provisions suitable for incorporation in local codes, standards, and practices.
- Research on performance criteria and supporting measurement technology for earthquake resistant construction.

The Federal Emergency Management Agency (FEMA) was formed by combining the Defense Civil Preparedness Agency, the Federal Insurance Agency, the Federal Disaster Assistance Administration, and the U.S. Fire Administration, and designated as the lead agency for NEHRP. Its role was to provide leadership in coordinating earthquake hazards reduction activities in the appropriate federal agencies and to assist State and local governments in planning and implementing their own programs. The other principal agencies were the U.S. Geological Survey (USGS), charged to conduct research on the nature of earthquakes, earthquake prediction, hazards evaluation and delineation, and induced seismicity, to evaluate earthquake predictions, and prepare national seismic risk maps; the National Science Foundation (NSF), charged to support fundamental research studies on earthquakes, and basic and applied research on earthquake engineering and policy; and NBS with the role cited above.

FEMA, USGS, and NSF requested and received budget increases to support their roles. NBS requested FEMA to fund through the FEMA budget the development, testing and adoption of seismic design and construction standards.

15.8.3 SEISMIC STANDARDS FOR BUILDINGS

Efforts to develop nationally applicable seismic design and construction provisions suitable for adoption by model building codes and state and local governments continued while NEHRP was being planned. With funding from

NSF, NBS consulted 30 private sector organizations to develop a plan for assessment and implementation of the tentative provisions [7]. Charles Thiel transferred to FEMA to lead its earthquake hazard mitigation activities and supported the organization in 1979 of the Building Seismic Safety Council (BSSC), under the auspices of the National Institute of Building Sciences (NIBS), to convene the expertise and interests needed to develop nationally applicable and acceptable seismic design and construction provisions. Ugo Morelli joined FEMA to become the program officer for the effort, and James Smith became executive director of BSSC. As BSSC came up to speed, and working with private sector and other agency experts convened by BSSC, CBT provided technical support for review and refinement of the tentative provisions [8], planning the trial design program for the tentative provisions [9], and preparing amendments to the tentative provisions for use in the trial designs [10].

E.V. Leyendecker led the Structures Division's Earthquake Engineering Group through the exciting initial years of NEHRP working effectively with colleagues in other federal agencies and the private sector and leading both earthquake engineering research and participation in the development of seismic design and construction provisions for buildings. In recognition of these efforts, Leyendecker received the Bronze Medal of the Department of Commerce in 1981, and the Silver Medal of the Department of Commerce in 1986. The review of the tentative seismic provisions provided an excellent opportunity for CBT staff to become familiar with the state of the art of knowledge and practice, their peers in research and practice, and priority needs for research. CBT participants included: Louis Cattaneo, Robert Chapman, Riley Chung, Patrick Cooke, Bruce Ellingwood, Thomas Faison, H.S. Lew, Richard Marshall, James Pielert, Timothy Reinhold, Lawrence Salamone, James Shaver, Stephen Weber, Kyle Woodward, and Charles Yancey. Weber's study, revealing the modest cost implications of the recommended provisions [11] as determined by the trial designs, was crucial to the subsequent issuance of the Executive Order requiring use of the provisions in federal construction and in adoption of the provisions in national standards and model building codes.

Since NBS had relinquished the funding of seismic standards studies to FEMA, and FEMA came to consider it more cost effective to fund BSSC to provide the technical secretariats for the various technical committees developing the provisions, CBT participation declined. James Harris, who left CBT in 1981 for private practice in structural engineering, continued to be active in BSSC and ASCE standardization activities and has become a nationally recognized leader. E.V. Leyendecker, who left CBT in 1986 to join the USGS, continued throughout the 1990s to play a lead role in development of the seismic hazard maps referenced by seismic design and construction standards.

BSSC completed The NEHRP Recommended Provisions for Seismic Regulations for New Buildings in 1985, and was funded by FEMA to continue their evolution in subsequent editions of 1988, 1991, 1994, 1997, and 2000. There was no immediate movement, following their issuance in 1985, towards adoption of the Recommended Provisions by national standards and model building codes. As described in the following section on ICSSC, CBT/BFRL was influential in achieving adoption of the Recommended Provisions.

15.8.4 INTERAGENCY COMMITTEE ON SEISMIC SAFETY IN CONSTRUCTION

At the start of NEHRP the White House directed FEMA to form an Interagency Committee on Seismic Safety in Construction (ICSSC) to assist the more than 30 federal agencies involved in construction in implementing earthquake hazards reduction elements in their ongoing programs. ICSSC was assigned the only output milestone for the program: to develop seismic design standards for federal construction and initiate their testing by federal construction agencies by 1980. ICSSC, with FEMA funding CBT to provide its technical secretariat, met this milestone [6]. Charles Thiel of FEMA chaired ICSSC from its inception in 1978 until he left federal service in 1982. Richard Wright of

CBT then chaired ICSSC until he retired from federal service in 1999. Subsequently, Shyam Sunder of NIST has chaired ICSSC and Steven Cauffman has provided its secretariat.

The federal agencies wished (by federal policy and for efficiency and economy) to use the same seismic design and construction practices for its construction as were generally used in the private sector and referenced by state and local building codes. However, legislation and Administration policy also required the federal agencies to use up to date seismic design and construction practices, and private sector consensus procedures for voluntary standards and model codes could be slowed by proprietary concerns. Therefore, ICSSC worked with the private sector in the BSSC and simultaneously developed and tested its own provisions [6, 12] to have a viable alternative if the BSSC effort failed. For his leadership in this work, James Harris received the Department of Commerce Bronze Medal Award in 1981 for this accomplishment.

In accord with the direction of the NEHRP Program Plan [5], ICSSC proceeded to develop a proposed Executive Order [13] requiring use of up to date seismic provisions in federal construction. The original proposed Executive Order, developed through many ballots by ICSSC agencies, covered new and existing buildings and lifelines. As consideration proceeded in the White House, its scope was reduced to new federal and federally assisted or regulated buildings for which up to date standards had been prepared (by BSSC and ICSSC) and for which the cost implications had been shown to be modest by trial designs.

The October 17, 1989, Loma Prieta earthquake in California renewed public, Administration, and Congressional interest in seismic safety. Using the ICSSC-developed proposal at hand, the President issued Executive Order 12699, Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction, on January 5, 1990. Federal agencies were able to proceed immediately to use ICSSC or BSSC provisions for their own buildings. Broader effect on seismic safety was achieved by the requirement that federally assisted construction, such as new homes with FHA or VA mortgages, be designed and constructed using standards considered appropriate by ICSSC. This federal mandate actually was welcomed by the national standards organizations and model building codes since it provided incentive for state and local governments to adopt and enforce up to date standards and codes to be eligible for federally assisted construction. ICSSC, BSSC and its member standards and model code organizations, collaborated to show equivalence of the 1991 Uniform Building Code to the 1988 BSSC Provisions and to develop and adopt changes based on the 1988 BSSC Provisions in the 1992 supplements to the SBCC Standard and BOCA National Building Codes. The NEHRP goal of making adequate seismic resistance available for all new U.S. building construction was achieved.

Diana Todd joined the CBT staff in 1990 to provide dynamic leadership for the ISCSC secretariat. ICSSC was much involved in support to federal agencies in implementation of EO 12699 for new buildings [14], support for the assessment of the equivalency of model building codes to the BSSC provisions [15] and the development of proposals for changes to the model codes, and in developing standards [16], and a proposal for an implementing executive order, for the seismic safety of existing federal buildings. FEMA provided sustained support for BSSC in developing guidelines for seismic evaluation and strengthening of existing buildings and for ICSSC in developing policies and practices for evaluation and strengthening of existing federal buildings.

Following the January 17, 1994, Northridge Earthquake, the President issued Executive Order 12941, Seismic Safety of Existing Federally Owned or Leased Buildings, on December 1, 1994. It adopted the standards [16] and called for agencies to inventory their owned and leased buildings and estimate the costs of mitigating unacceptable seismic risks. ICSSC developed guidance to the federal agencies on implementation of the executive order [17] and collaborated with BSSC in a trial design program, using federal buildings, of the costs implementing the BSSC-produced NEHRP

Guidelines for the Seismic Rehabilitation of Buildings.

In September 2000, FEMA submitted, A Report to the Congress: Toward Earthquake Resistant Federal Buildings, to the Office of Management and Budget. This report included an inventory of Federal Buildings, compiled by John Hayes and Steve Sweeney of the U.S. Army Civil Engineering Research Laboratory. The report, prepared by Degenkolb Engineers under the leadership of Ugo Morelli of FEMA and Chris Poland of Degenkolb Engineers. During its preparation, the report was extensively reviewed and commented on by the ICSSC.

ICSSC Subcommittee 1 (Standards for New and Existing Buildings), under the leadership of H. S. Lew drafted an Executive Order entitled, Seismic Rehabilitation of Federal Buildings, to implement the recommendations of the Report to Congress. Ugo Morelli of FEMA and Charles Gutberlet of the U. S. Army Corps of Engineers prepared the draft Executive Order. The Executive Order was approved by the ICSSC Full Committee and submitted by FEMA to the Office of Management and Budget with the Report to Congress in September 2000.

ICSSC organized federal teams to investigate performance of buildings and lifelines in important earthquakes [18, 19, 20] and developed recommendations for ICSSC activities to mitigate effects of future earthquakes.

15.8.5 EARTHQUAKE ENGINEERING EXPERIMENTAL FACILITIES

At the request of the White House Office of Technology Policy, the National Research Council (NRC) in 1984 organized a committee led by H. Norman Abramson and published a report on Earthquake Engineering Facilities and Instrumentation [21]. It concluded:

> *The irreducible need for full-scale data on the behavior of earthquake-impacted multistory structures requires that the nation have experimental facilities able to test such structures across a range from damage initiation to collapse.*

It recommended:

> *The federal government should undertake, on an accelerated basis, planning aimed at developing a major national earthquake engineering experimental/test facility.*

FEMA, NSF and NBS funded CBT in 1985 to conduct the planning. CBT defined a four year, four phase study covering research needs, facility characteristics, siting and management. The first phase, research needs, included collecting background data, commissioning research needs recommendations from six expert consultants, a workshop of researchers, professionals and industry representatives to define research needs, and commissioning another NRC Panel, chaired by James Beavers, to advise in the study. The CBT report [22] presented a five year research program for a National Earthquake Engineering Experimental Facility (NEEEF).

The report of the NRC Panel [23] concluded;

. . . it is now clear to the panel that the National Bureau of Standards' current approach, which focuses on a particular facility, cannot be continued because of broader issues and needs that must first be considered in such a feasibility study.

Essentially, the Beavers panel disagreed with the Abramson panel that there should be a plan for a single, major, national facility. Apparently, the principal research universities objected that at most one of their number (the facility might go to a national laboratory instead of a university) would monopolize the state of the art earthquake engineering experimental facilities. While the NEEEF study did not need to focus on a single facility, NEHRP was not hearing good support from the earthquake community for its continuation by CBT; hence, it was terminated.

The need for improvement of U.S. earthquake engineering experimental facilities remained and was highlighted by uncertainties in understanding of structures performance in the 1989 Loma Prieta and 1994 Northridge earthquakes. The 1994 reauthorization of NEHRP (PL 103-374) called for the President to "conduct an assessment of earthquake engineering research and testing capabilities in the United States." Informed by the experience ten years before, NSF and NIST commissioned the Earthquake Engineering Research Institute to perform the assessment [24], which was chaired by Daniel Abrams with James Beavers as project manager. It gave highest priority to modernizing existing laboratories and led to the $84 million George W. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) that NSF began in 2000.

15.8.6 STANDARDS FOR LIFELINES

Lifelines are the transportation (highways, airports, railways, waterways, ports and harbors) and utility systems (electric power, gas and liquid fuels, telecommunication, water, and sewer) that support most human activities. Lifeline failures during earthquakes cause losses of life, property, and income as well as environmental damages. Lifeline failures also result in post-earthquake fires, hinder emergency and rescue operations, and delay recovery and reconstruction. While by 1990, there were up to date seismic provisions available for building codes, there were no nationally accepted standards or guidelines for lifelines except for highway structures and nuclear facilities. Public Law 101-614, the 1990 National Earthquake Hazards Reduction Program Reauthorization Act stated:

> *The Director of the Agency (FEMA), in consultation with the Director of the National Institute of Standards and Technology, shall submit to Congress, not later than June 30, 1992, a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines. The plan shall include recommendations of ways Federal regulatory authority could be used to expedite the implementation of such standards.*

In response to the mandate, FEMA funded NIST/BFRL to conduct the planning. FEMA organized a Steering Group chaired by Ronald Eguchi, then chairman of the Technical Council on Lifeline Earthquake Engineering, to advise on the planning. The Steering Group approved the process for planning which included commissioning drafts for the various lifeline types from private sector experts and holding a planning workshop from September 25-27, 1991, of over 50 experts predominantly from the private sector and academia. The resulting plan [25] called for an 8 year program totaling $54.7 million dollars. Implementation would be primarily through the existing voluntary standards system with an Executive Order requiring federal agencies to adopt and use seismic standards for federal and federally assisted or regulated new and existing lifelines.

A draft plan, based on the workshop report, was reviewed by the NEHRP Advisory Committee in January 1992, and was not supported by the Advisory Committee or FEMA. FEMA and NIST worked with a subgroup of the Advisory Committee to develop a revised plan that was approved by the White House and submitted to Congress [26]. It called for working with the private sector to develop guidelines and standards for lifelines, but did not give a schedule or estimate funding required. Then, under the auspices of the Interagency Committee on Seismic Safety in Construction (ICSSC) a Lifeline Policymakers Workshop was held by the American Society of Civil Engineers (ASCE) (27) which estimated that a five year program amounting $16 million was required. FEMA has supported the formation by ASCE of the American Lifeline Alliance to work on the development of guidelines and standards for lifelines.

15.8.7 NEHRP MANAGEMENT

CBT/BFRL as a principal agency in NEHRP was fully involved in its planning and management activities. These included several cycles of strategic planning and planning for special supplementary research funding following the 1989 Loma Prieta and 1994 Northridge earthquakes to assure exploitation of the opportunities to improve knowledge and practice from lessons that could be learned by studying earthquake mechanisms, performance of structures, societal behavior and emergency management procedures in the earthquakes. CBT/BFRL's influence on plans and public policies was proportionally much greater than its two percent share in NEHRP appropriations because its representatives for planning and Congressional testimony were knowledgeable in earthquake engineering.

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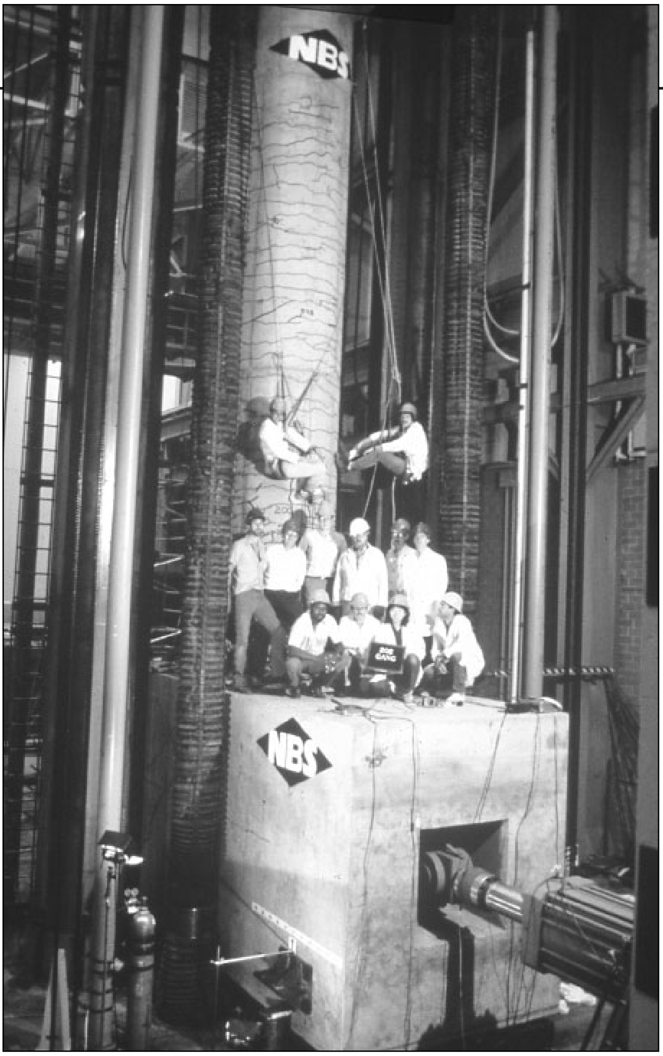
15.9 EARTHQUAKE RESEARCH

15.9.1 SOIL LIQUEFACTION

CBT formed a Geotechnical section led by Felix Yokel in the mid 70s as part of the Structures and Materials Division. One of it major focuses was the prediction of soil liquefaction under strong ground shaking which had been shown to be a major factor in damages to buildings and lifelines. Yokel recruited William Kovacs, Riley Chung, and Larry Salomone to join CBT and involved external experts such as Ricardo Dobry in the section's research. The widely used Standard Penetration Test (SPT) had been shown to correlate with liquefaction potential, but variability in the test procedures made predictions unreliable. A thorough study of the test procedures and the energy delivered to the sampling device [1] led to recommendations to improve ASTM Standard D1586 for the test and reduced variability of results. Cooperation with Japanese researchers through the US/Japan Panel of Wind and Seismic Effects led to joint studies of US and Japanese testing procedures [2] so that Japanese data on liquefaction in earthquakes could be used with U.S. data and test methods for prediction of seismic liquefaction potential of soil deposits. Laboratory and field studies of pore water pressure build up in shaken soils led to identification of the critical cyclic strain as the mechanism leading to liquefaction [3].

Threats to the existence of CBT and cuts in its funding in the 80s led to the departure of most of its geotechnical engineers and the end of the section. With increased funding for earthquake engineering at NIST following the 1989 Loma Prieta and 1994 Northridge earthquakes, Riley Chung returned to BFRL to lead its Earthquake Group and recruited Ronald Andrus to resume geotechnical research. Andrus and Chung performed important work to develop the shear wave velocity method [4] for predicting liquefaction potential. However, restricted funding in the late 90s caused BFRL again to terminate geotechnical research since it could not support a world class program. In spite of limited resources and work that started and stopped, twice, CBT's and BFRL's researchers succeeded in making major contributions to reliable and economical methods for identifying liquefaction susceptible soil deposits.



Full-scale test of bridge column performed in BFRL's large-scale structural test facility with its 53 MN universal structural testing machine that can test structural components up to 17.7 m in height.

15.9.2 BRIDGE COLUMN REINFORCING REQUIREMENTS

As a result of the 1971 San Fernando earthquake, design requirements for bridge columns in seismic zones were modified. This included new requirements for the anchorage of longitudinal reinforcing steel into foundations. However, the adequacy of these design modifications was not verified. The Large Scale Bridge Column Project was initiated by the Center for Building in the early 1980s to provide the necessary verification. This project, led by William Stone, consisted of two full-scale bridge column tests; one column was designed to fail in flexure and the other was designed to fail in shear. The columns were designed to the CALTRANS (California Department of Transportation) specifications. The challenges arose from the size of the test specimens and the need to apply lateral (seismic) loads in addition to vertical (gravity) loads. The tests were designed to use the existing 53 MN universal testing machine to apply the vertical load to simulate the mass of the bridge superstructure. A 14 m high post-tensioned reaction wall and rail system had to be constructed for the application of the lateral loads. The series of column tests was the first of its kind and as such, provided important benchmark data [5]. The tests verified the adequacy of the revised CALTRANS design specifications. In addition, Geraldine Cheok tested companion 1/6-scale bridge columns and the results indicated that the behavior of full-scale bridge columns could be extrapolated from small-scale bridge column tests. This finding suggests that the high costs associated with full-scale tests are not always necessary and less expensive small-scale tests may be sufficient.

15.9.3 PRECAST CONCRETE FRAMES

Precast concrete frame construction has not been used extensively in high seismic regions of the United States, despite its potential benefits in construction speed and quality control. This is because building code requirements (e.g., Uniform Building Code, UBC) have been based on past experience with cast-in-place construction and regard precast construction as an "undefined structural system" which must be shown to be equivalent to cast-in-place systems and to provide sufficient lateral force resistance and energy absorption capacity. Also, a precast concrete framed structure collapsed in the 1964 Anchorage, Alaska earthquake.

Therefore, in 1987, CBT initiated a project to study the performance and development of moment-resisting precast beam-column connections. The challenge was to develop a connection that was economical, easy to construct, and capable of resisting the cyclic inelastic deformation caused by earthquake loadings. Based on initial tests in the study, a post-tensioned precast connection appeared to be viable. These early results caught the interest of Charles Pankow Builders, which provided funding through the American Concrete Institute Concrete Research Foundation to further develop the post-tensioned concept. Close collaboration between William C. Stone, Geraldine S. Cheok, and H. S. Lew of NIST, Dean Stephan and David Seagren of Pankow Builders, and John Stanton of the University of Washington, resulted in three different designs. The most viable design combined the use of low strength reinforcing steel and high strength prestressing steel - a hybrid connection. Based on tests conducted by NIST [6], design guidelines for precast hybrid connections were developed. These guidelines and results were used to obtain approval from the International Conference of Building Officials Evaluation Service for the construction of hybrid connections in seismic zones.


Thirty-nine-story precast concrete building in San Francisco.

In addition, the American Concrete Institute (ACI), which is responsible for the national standard for reinforced concrete structures, developed a provisional standard for this system. Several structures using the hybrid connections have been constructed and several more are under consideration. The hybrid connection allowed for construction of a $128-million, 39-story building in San Francisco (see drawing). This building will be the tallest concrete frame building to be built in a high seismic region. Recognition of the innovation of the work was reflected in the awards received - ACI Structural Research Award for Cheok and Stone in 1997, Department of Commerce Bronze Medal for Cheok in 1997, Finalist in Civil Engineering Research Foundation Charles Pankow Award for Innovation in 1998, Maryland Young Engineer Award for Cheok in 1997, and Department of Commerce Silver Medal for Cheok, Lew and Stone in 2001.

15.9.4 REHABILITATION OF WELDED STEEL MOMENT FRAME CONNECTIONS

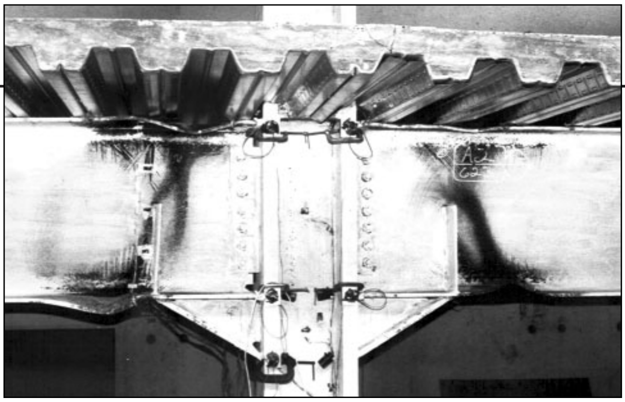
Steel framed buildings traditionally have been considered to be among the most seismic resistant structural systems. The January 17, 1994 Northridge earthquake, however, caused unexpected damage to many welded steel moment frame buildings. In general, the damage was confined to beam-to-column connections that suffered brittle fracture in the flange welds. In response to these failures, NIST initiated research into methods to modify existing buildings to improve their seismic performance. A collaborative research effort led by John Gross was undertaken and involved Nestor Iwankiw of AISC, Michael Engelhardt of The University of Texas, Chia-Ming Uang of the University of California, San Diego, and Kazuhiko Kasai of Lehigh University. Three methods to reduce the stresses at the beam-to-column connection were studied: 1) welded haunch, 2) reduced beam section, and 3) bolted bracket. Eighteen full-scale tests were conducted on subassemblages representing interior joints, both with and without a concrete floor slab. The result of this multi-year effort was the publication of comprehensive guidelines for the seismic rehabilitation of existing welded steel frame buildings - AISC Design Guide No. 12 [7]. The guidelines provide experimentally-validated response prediction models and design equations for the three connection modification concepts that shift loading from the weld joints into the beams, thus enabling the structure to absorb the earthquake's energy in a non-brittle manner. AISC Design Guide No. 12 has been cited by the FEMA document, Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment Frame Buildings. John Gross received the Bronze Medal Award of the Department of Commerce in 2001 for his leadership of this study.

15.9.5 TEST METHODS FOR PASSIVE AND ACTIVE SEISMIC ENERGY ABSORPTION

Structural control devices, such as seismic isolation and passive energy dissipators, have been installed in numerous structures throughout the world and have proven to be effective in reducing both motions and forces during earthquakes and strong winds. Still these devices are generally produced in small quantities, specifically for each application. To guarantee that the devices will perform as the designer expected, many building codes and guidelines recommend that the devices be tested before installation. While some of these standards describe a limited number of specific tests, widely accepted test standards do not yet exist. Before his untimely death in 1993, Albert Lin recognized the need for comprehensive and consistent test standards. Such standards are useful to designers, manufactures, and contractors, since they will make the process of validating these devices consistent. To address the issue, BFRL developed two sets of testing guidelines and has worked to experimentally verify the guidelines completeness.

BFRL researchers began the effort with the development of guidelines for testing seismic isolation systems [(8] entitled: Guidelines for Pre-Qualification, Prototype, and Quality Control Testing of Seismic Isolation Systems. Harry W. Shenton, III, developed this set of guidelines, in consultation with a technical review committee that consisted of designers, manufactures, and academicians who are experts in the field. A draft of the guidelines was reviewed by a broader group of seismic isolation experts, and their comments were incorporated into the final version of the guidelines. The American Society of Civil Engineers (ASCE) is in the process of developing a national consensus standard based on the NIST-developed isolation device testing guidelines. The consensus standard is currently (2002) in the balloting phase.

To verify the completeness of the isolation testing guidelines, Andrew Taylor, working with Gregory Bradley and Peter Chang, both from the University of Maryland, began experimental tests on elastomeric isolators. They performed a series of tests to determine the bearing's ultimate compressive strength, failure mode, and the effects of model scale on the response [9]. The experimental results were compared with numerical simulations, and used to improve the accuracy of the numerical models. The effort is continuing with a series of tests that will be performed on isolators with known



Full-scale test of welded haunch modification to steel moment frame connection

manufacturing flaws. These tests will also investigate how accurately such flaws can be numerically modeled and how adversely they affect the performance of the isolators. The results of these tests are expected to expose any inconsistencies, omissions, or other unforeseen problems with the testing procedures, and will provide useful data for the development of performance-based seismic design.

While seismic isolation is generally accepted by earthquake engineering profession and recognized in the building codes in high-seismic areas, passive structural dampers are still gaining acceptance and semi-active devices are still in the development phase. To address the needs related to these newer technologies, BFRL research is continuing with efforts to develop and improve test methods, design procedures, and analytical tools for passive and semi-active structural dampers. Fahim Sadek and Michael A. Riley followed a procedure similar to that used to develop the isolation device testing process of developing these guidelines. Analytical results led to better methods for determining the number of equivalent cycles necessary for testing structural control devices.

In addition to the development of testing guidelines, this program has produced a wide variety of other structural control related documents. Work by Fahim Sadek, Riley Chung, Andrew Taylor, and Bijan Mohraz of SMU led to publication of an innovative, simplified method for designing tuned mass dampers. BFRL researchers have also developed improved design procedures for passive dampers [10], which are intended to replace current procedures that may produce non-conservative designs in some cases. Research on semi-active control devices and the on-going collaboration with researchers at the Polytechnic School of Tunisia is leading to advancements in non-linear control laws and control of non-linear structures [11]. Andrew Taylor received the Bronze Medal Award of the Department of Commerce in 1996 for his contributions to development of the testing guidelines.

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