CONFERENCIAS 1ª SESION

THE PRESENT AND THE FUTURE OF EXPERIMENTAL INVESTIGATION IN THE UNITED STATES OF AMERICA

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Abstract

In this paper, the objectives of structural engineering testing are summarized, with particular emphasis on the field of earthquake engineering. Basic equipment requirements for structural testing laboratories are reviewed in the light of those objectives. The current state of structural engineering testing practice in the United States of America is discussed with respect to those objectives. Future trends in structural testing laboratories and equipment in the United States of America are identified, thereby addressing as well possible future trends in experimental structural engineering investigation in Mexico. Finally, the relationship between structural engineering testing and available funding sources is discussed, and suggestions are made for increasing the involvement of the private sector in structural engineering testing.

1.0 SCOPE AND OBJECTIVES

The general topic of experimental structural investigation in the United States of America is far too broad to be covered completely by a single paper such as this. The paper will therefore focus on the first two stated purposes of this CENAPRED Workshop:

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- To present the current state of the practice in structural testing laboratories in Mexico, Japan, and the United States of America
- To identify needs for testing laboratories and equipment in Mexico, as well as future trends in experimental investigations in Mexico.

In this paper, the objectives of structural testing are summarized, with emphâsis on the field of earthquake engineering. Basic equipment requirements for structural testing laboratories are reviewed in the light of those objectives. The current state of structural engineering testing practice in the United States of America is discussed with respect to those objectives. Future trends in structural testing laboratories and equipment in the United States of America are identified, thereby addressing as well possible future trends in experimental structural engineering investigation in Mexico. These issues must be addressed from the viewpoint of available technology, and also available funding.

2.0 FUNDAMENTAL OBJECTIVES OF EXPERIMENTAL TESTING IN STRUCTURAL ENGINEERING

Experimental testing in structural engineering can be carried out to further many different objectives:

- to evaluate materials
- to educate engineers, architects, and testing laboratory personnel
- to refine testing equipment
- to evaluate the behavior of mechanical equipment
- to evaluate the behavior of structural elements, subassemblages, or systems
- to demonstrate the validity of a structural design or concept
- to develop and refine analytical models

Understanding of these objectives is important, because the objectives of testing determine the most appropriate equipment and procedures for any particular structural engineering test. In the remainder of this section, examples will be given of each of these objectives.

2.1 Structural Testing to Evaluate Materials

The most basic function of structural testing is to evaluate materials. Examples of this are routine testing of concrete cylinders or cubes. This type of testing is useful for education, and also can provide the financial income to permit more complex types of testing.

2.2 Structural Testing to Educate Engineers, Architects, and Laboratory Personnel

While education of engineers, architects, and testing laboratory personnel should not be the only function of a structural testing laboratory, it is an essential one. Education in proper testing techniques increases the reliability of routine tests, makes it possible to carry out more complex tests, and makes it possible to start new structural testing laboratories.

2.3 Structural Testing to Refine Test Equipment

Routine material testing usually requires nothing more complex than a universal testing machine. As is discussed further below, however, more complex structural testing requires more complicated equipment. As it is introduced, this equipment must be tested and refined.

2.4 Structural Testing to Evaluate the Behavior of Mechanical Equipment

Some structural engineering testing is intended to evaluate the proper functioning of mechanical equipment under seismic conditions. Such approval may be required by code-writing bodies, or may be used by private industry in qualifying equipment.

2.5 Structural Testing to Evaluate the Behavior of Structural Elements, Subassemblages, or Systems

In the environment of a structural research facility, the most common objective of structural testing is to evaluate the behavior of structural elements, subassemblages, or systems. Examples of such testing are familiar to many of the participants at this Workshop: beams; columns; beam-column connections; walls; frame or wall assemblages; and complete buildings.

2.6 Structural Testing to Demonstrate the Validity of a Structural Concept

Although structural testing whose primary objective is to evaluate the behavior of structural elements can also be used to demonstrate the validity of a structural concept, the latter objective is sometimes considered separately. Examples of this are the testing which accompanied the development of the eccentric braced frame in steel construction (Engelhardt 1989). A general demonstration of the seismic resistance of eccentric braced frames was at least as important as determination of the exact characteristics of member response.

2.7 Structural Testing to Develop and Refine Analytical Models

Since the early 1970's, when practical computer-oriented methods of nonlinear structural analysis were first proposed, structural testing has been used to develop and refine analytical models. Nonlinear models are typically characterized by a so-called "backbone stiffness" (initial and inelastic), by a strength envelope, by rules for stiffness and strength degradation, and by rules for small-displacement cycles within previously established envelope (Ghosh 1991).

All these model characteristics can be developed empirically using structural testing. For this purpose, complex loading histories are often adopted, involving cyclic loads or displacements with monotonically increasing maxima, combined with lower-amplitude cycles. Such complex histories, while scarcely resembling response to real earthquakes, permit a large amount of information to be extracted from each test specimen.

3.0 EQUIPMENT REQUIREMENTS FOR STRUCTURAL ENGINEERING TESTING LABORATORIES

Clearly, any structural testing laboratory needs basic building facilities, such as a work area, sufficient shelter, and adequate supplies of water and electrical power. It also needs the following equipment:

- transportation equipment
- loading equipment
- data acquisition equipment
- data reduction and reporting equipment

In this section, equipment requirements in each of those areas are discussed in the light of the above objectives of structural testing. In view of the many possible objectives of structural testing summarized above, it should be apparent that no single set of equipment is ideal. The purpose of this section is to clarify the criteria for choosing among different options in each area. In considering the comparative costs of different types of equipment, it is worthwhile noting that over its useful life, a piece of equipment will usually have an operation and maintenance cost of from 50% to 100% of its original price.

3.1 Transportation Equipment

Depending on the size and weight of the equipment to be moved within a laboratory, anything from hand carts to motorized tractors may be needed. In addition, the potential value of an overhead crane cannot be underestimated. An overhead crane, operating on rails suspended over the laboratory, is the single most useful piece of equipment for moving material in the laboratory. Overhead cranes are widely produced, with prices ranging from $5,000 to $10,000 (US dollars).

3.2 Loading Equipment

Loading equipment for structural engineering testing can conveniently be categorized as follows:

- universal testing machines
- separate hydraulic pumps and actuators
- reaction devices (frames, tie-down floors, walls)
- shaking tables
- pseudo-dynamic test equipment

3.2.1 Universal Testing Machines: The most common piece of equipment found in any testing laboratory is a universal testing machine, whose loading equipment consists of a electric-powered pump, connected to a hydraulic actuator which is mounted in a stiff frame, arranged to permit the application of tensile or compressive load to a specimen held within the frame. While such machines are convenient and well suited for routine tensile or compressive tests of small specimens, there are several reasons why they might not be the first purchase in equipping a structural engineering testing laboratory: Such machines are usually more expensive than the sum of their individual components, and can easily cost in excess of $50,000. They are usually too heavy to move about the laboratory. They are usually too small to accept specimens representing full-sized structural components. Finally, because they usually incorporate many different components, they can be rendered useless by a mechanical problem with any single component.

3.2.2 Separate Hydraulic Pumps and Actuators: Separate hydraulic pumps and actuators avoid many of the disadvantages of universal testing machines. They are versatile, portable, and relatively inexpensive. A small-capacity electric pump, several hydraulic actuators, and all required hoses and connectors would cost about $5,000. This type of equipment is produced in great variety, and repairs and replacement parts are readily available. Their principal disadvantage is that separate reaction devices must be used to restrain the specimens.

Hydraulic equipment can either be controlled manually, or by a closed-loop feedback system. In manual-controlled systems, the pump can either be hand-operated, or electrical. Such systems, while very simple, are very useful. If the reaction system is sufficiently stiff, they can operate essentially as displacement-control loading systems. Servo-controlled equipment compares a selected response quantity (either force or displacement) with the desired value, and automatically positions a hydraulic valve so that the actuator applies the correct load. Such systems offer more speed and the possibility of automatic generation of loading histories. Their disadvantage is increased cost and complexity. A servo-controller would add about $2,000 to the cost of the hydraulic system noted above, and it would represent an additional maintenance item.

Testing in which a specimen's load or displacement history is controlled throughout the test, at a slow rate, is referred to in general as "pseudo-static testing." It is by far the most common type of structural testing conducted in the United States of American at the present time.

3.2.3 Reaction Devices: These normally consist of frames or similar tie members. As specimen size and capacity increase, the strength and stiffness requirements of reaction devices may make it advisable to use a reaction floor. Lateral load tests on tall specimens can be facilitated by the use of integral reaction walls.

3.2.4 Shaking Tables: These were first implemented in the 1970's as a way of reproducing the effects of earthquakes in real time in the laboratory. They are essentially closed loop loading systems, operating under acceleration control, that can move a specimen in one, two, or even three axes. The United States of America has several medium-sized shaking tables, and many smaller ones.

Shaking table testing has one important advantage: the testing is a close representation of an actual earthquake.

It also has several disadvantages:

- It often requires small-scale testing. A shaking table's acceleration, velocity, and displacement capacity are limited, respectively, by its actuator capacity, by its pumping and servo-valve capacity, and by its actuator displacement limits. Actuator capacity is often insufficient to permit the testing of full-sized specimens. As a result, small-scale models must be used; the time scale must be altered, and additional mass placed on the specimens to produce the proper force levels.

- It can be inaccurate. Errors in a shaking table's feedback control systems, or dynamic interaction with the surrounding soil-structure system, can produce errors between the desired input motion and that which is actually applied. For some specimens, and in some frequency ranges, such errors can be so severe as to make a shaking table almost useless.

- o It happens very quickly. Because the test takes place at or even faster than an actual earthquake, there is no opportunity to stop the test to observe the behavior of the specimen, or to prevent a catastrophic failure.

- o It is expensive. Initial costs of a shaking table are about $1 million, with corresponding operation and maintenance costs.

3.2.5 Pseudo-Dynamic Loading Equipment: The concept of pseudo-dynamic testing was first proposed in Japan in the early 1970's. Pseudo-dynamic testing combines physical testing with an analytical model of the specimen. Consider a nonlinear, multi-degree-of-freedom system, whose accelerations, velocities, and displacements are known at some time. If the ground acceleration is known as a function of time, and if the structure's resisting force vector is known, the structure's response at the next time step can be calculated. In pseudo-dynamic testing, the resisting force vector is measured experimentally at each step; the acceleration and damping forces are calculated; and the specimen's response is imposed step-by-step using hydraulic actuators. The test takes place much more slowly than an actual earthquake.

Pseudo-dynamic testing offers a few advantages over shaking-table testing, chiefly because tests can be stopped to observe the behavior of the specimen or to avoid a catastrophic failure.

It also has some disadvantages:

- o Control of the specimen is complex. Because of the finite precision of displacement and load transducers, small measurement errors can cause an erroneous specimen response, or even a loss of control over the specimen.

- o The behavior of the specimen is not known before the test. Because the specimen's response depends on the known input motion, but also on its own unknown inelastic response characteristics, neither the load history nor the displacement history can be predicted in advance. As a result, it is difficult to predict the hysteretic response that will result from a given input motion.

- o Pseudo-dynamic testing is as expensive as shaking-table testing.

3.3 Data Acquisition Equipment

Data acquisition equipment for structural engineering testing can conveniently be categorized as follows:

- o hand-operated equipment (load indicators, dial gages)
- o electronic equipment

3.3.1 Hand-Operated Data Acquisition Equipment: Common examples hand-operated data acquisition equipment are the dial gage and pressure meter. Such equipment is reasonably inexpensive (about $200) and reliable. However, it has the important disadvantage of requiring a human operator. It is therefore unsuitable for tests at high load rates, for tests involving brittle behavior, or for fatigue testing.

3.3.2 Electronic Data Acquisition Equipment: This includes such items as strain gages, load cells, and displacement transducers. These have many potential advantages over hand-operated data acquisition equipment: they are usually more accurate; they can be read much more rapidly; they can function automatically; and perhaps most important, the data do not have to be transcribed by hand. These systems normally include the following items:

- o a power supply
- o load or displacement transducers
- o a scanner to read the transducers
- o analog-to-digital conversion circuitry to digitize the readings

The analog to digital conversion permits the data to be stored directly in the microcomputer. Assuming a microcomputer to be available, the additional cost for a power supply and conversion circuitry is about $2,000. Electrical transducers themselves typically cost about $200 each, the same as the hand-operated ones.

Given its many advantages over hand-operated equipment, and its decreasing cost, electrical data acquisition equipment is probably preferable for most testing applications.

3.4 Data Reduction and Presentation Equipment

In today's microcomputer environment, the easiest way to reduce and present data is using spreadsheet-type programs. Tasks that formerly took many weeks, and were troubled by human error, can now be accomplished reliably in minutes.

4.0 CURRENT STATE OF STRUCTURAL ENGINEERING TESTING PRACTICE IN THE UNITED STATES OF AMERICA

Structural engineering testing is now conducted in a wide range of laboratories throughout the United States of America:

- o commercial materials testing laboratories
- o private testing laboratories (CTL, Batelle, Southwest Research)
- o university laboratories

These laboratories use different combinations of the testing equipment discussed above, as appropriate to fulfill the objectives of the testing.

4.1 Testing to Evaluate Materials

In the United States of America, testing to evaluate materials is conducted primarily at commercial testing laboratories. Testing equipment typically consists of universal testing machines, electronic data acquisition equipment, and microcomputer data reduction and presentation equipment.

4.2 Testing to Educate Engineers, Architects, and Testing Laboratory Personnel

In the United States of America, testing for educational purposes is conducted primarily at university testing laboratories. Testing equipment typically consists of universal testing machines, electronic data acquisition equipment, and microcomputer data reduction and presentation equipment.

4.3 Testing to Refine Test Equipment

In the United States of America, testing to refine test equipment is conducted at university testing laboratories, and at the laboratories of companies developing the equipment. At the present time, most types of test equipment discussed above may be regarded as fully tested technologies, and are no longer undergoing developmental testing. Shaking tables and pseudo-dynamic test equipment, however, are still undergoing developmental testing, with the following goals:

Shaking tables:

- o increased reliability
- o active control of rotations as well as translations
- o increased accuracy in control systems

Pseudo-dynamic testing:

- o increased accuracy in control systems
- o increased stability in integration methods
- o increased speed of testing
- o increased reliability
- o two- and three-dimensional testing

4.4 Testing to Evaluate the Behavior of Mechanical Equipment

In the United States of America, testing to evaluate the behavior of mechanical equipment is generally conducted at specialized private laboratories such as Batelle or Southwest Research. Such testing generally involves high-frequency dynamic loads, applied through a small shaking table generally capable only of sinusoidal motion. A piece of equipment's performance is evaluated based simply on whether or not it continues to function after the shaking. Therefore, the data acquisition system, which is electronic, is used only to monitor the load.

4.5 Testing to Evaluate the Behavior of Structural Elements

In the United States of America, testing to evaluate the behavior of structural elements is conducted primarily in university testing laboratories. Testing is primarily pseudo-static. Using either manually controlled or servo-controlled hydraulic loading systems, specimens are subjected to pre-programmed loading histories.

Evaluation of the behavior of structural elements is usually carried out using pseudo-static testing, in which the displacement history of the specimen is determined before the test. Because shaking table testing and pseudo-dynamic testing do not permit prediction of the load or displacement history, and because they are much more expensive than pseudo-static testing, they are not often used to evaluate the behavior of structural elements.

4.6 Testing to Demonstrate the Validity of a Structural Design or Concept

In the United States of America, testing to evaluate the validity of a structural design or concept is conducted primarily in university testing laboratories. Initial testing is usually pseudo-static. Using either manually controlled or servo-controlled hydraulic loading systems, specimens are subjected to pre-programmed loading histories.

Final demonstration of the validity of a structural design or concept, however, is usually carried out using shaking table or pseudo-dynamic testing. Because it resembles an actual earthquake loading more than does pseudo-static testing, shaking table or pseudo-dynamic testing is often viewed as a more convincing earthquake simulation. This perception would seem justified in the case of a full-scale specimens tested on a shaking table. However, it is less justified when small-scale shaking table specimens are used, or when pseudo-dynamic procedures are employed.

Nevertheless, shaking table or pseudo-dynamic testing is often used as a demonstration of the validity of structural testing in general. Examples of this may be found in the United States of America - Japan coordinated testing programs. In each of these (reinforced concrete, structural steel, and masonry), pseudo-dynamic testing was used not only to demonstrate the validity of a structural concept, but as a kind of verification of the overall validity of the testing program. In the author's opinion, this verification is sometimes more necessary from the viewpoint of public relations, than for the actual technical knowledge gained. In such cases, the potential public relations benefits obtainable as a result of shaking table or pseudo-dynamic testing must be carefully weighed against the high costs of such testing.

4.7 Testing to Develop and Refine Analytical Models

In the United States of America, testing to develop and refine analytical models is conducted primarily in university testing laboratories. Testing is primarily pseudo-static. Using either manually controlled or servo-controlled hydraulic loading systems, specimens are subjected to pre-programmed loading histories. This permits experimental verification of the stiffness, strength, degradation, and low-level cycling behavior of analytical models.

As noted before, in shaking table and pseudo-dynamic testing the specimen's load and displacement history are not known in advance. These types of testing are therefore not very useful for developing and refine analytical models.

5.0 FUTURE TRENDS IN STRUCTURAL ENGINEERING TESTING PRACTICE IN THE UNITED STATES OF AMERICA

5.1 Technological Trends in Structural Engineering Testing in the United States of America

In the United States of America, structural testing practice developed rapidly as a result of strong federal government funding for earthquake engineering research in the 15 years following the 1971 San Fernando Earthquake. One of the landmarks in that development was the series of United States of America - Japan cooperative research programs. As a result of those programs, considerable information has been gained about the relationship between material testing, structural element testing, large-scale building testing, and analytical model development (Sozen 1988, Noland 1990).

In the past 20 years, structural testing in the United States of America has achieved three important qualitative advances:

- o microcomputer technology
- o the shaking table
- o pseudo-dynamic testing

The first of these is by far the most significant, and the other two would probably not have been achieved without it. In the past 20 years, the cost (corrected for inflation) of a computer system capable of performing data acquisition, data reduction, data presentation, and analytical comparisons, has decreased by a factor of about 50.

This tremendous decrease in the real cost of the computations associated with structural engineering testing has made possible the development of many new testing laboratories, and also the development of large-scale testing facilities. Both types of development have resulted in an increased demand for research funding.

These technological advances have produced many questions about the future direction of structural testing:

- o What types of testing (e.g., pseudo-static versus shake table) should laboratories conduct?

- o Should structural testing be conducted in large centers, or in many smaller facilities?

These questions are posed in technological terms. However, they have implications beyond technology, which must be addressed in formulating answers. These broader implications have to do primarily with the financial resources that support structural engineering testing in the United States of America.

5.2 Trends in Structural Engineering Research Funding in the United States of America

A natural consequence of the technical gains of the last 20 years has been the maturation of structural engineering testing as a field. While new information is still to be gained, it is unlikely that the field will experience qualitative changes as significant as the development of microcomputer technology, of the shaking table, or of pseudo-dynamic testing.

As a result of this maturation, continued funding for structural engineering testing is now at a much lower level, in real dollars, than it was 20 years ago. The increased demand for research funding, coupled with decreases in real funding, has created conflicts which are now being experienced throughout the United States of America.

- Because all universities (public as well as private) receive a smaller part of their income from governmental sources, there is increased pressure on universities and university faculty to establish structural testing laboratories and compete for a shrinking pool of available public and private research funds.

- The technical feasibility of very expensive testing laboratories (large shaking tables and pseudo-dynamic testing facilities) creates a demand for their establishment and continued support.

5.3 Future Directions for Structural Engineering Testing in the United States of America

Because these conflicts are institutional as well as technical, they are difficult to resolve. In the United States of America, the pluralism of the political process makes it difficult for the federal government to establish and fund large research centers for structural engineering testing on a long-term basis. It is therefore more probable that testing will continue at a large number of smaller research facilities, and will be primarily pseudo-static rather than shaking-table or pseudo-dynamic. Future trends in structural engineering testing must be directed at achieving the following two goals:

- To achieve more efficiency in pseudo-static structural engineering testing

- To develop alternative funding sources for structural engineering testing

5.3.1 To Achieve Increased Efficiency in Pseudo-Static Structural Engineering Testing: Assuming that most structural engineering testing in the United States of America will continue to be conducted on a pseudo-static basis at many different research facilities rather than a few large ones, ways must be found to achieve an increased quality and quantity of results, for the same cost. These goals can be achieved through steps such as the following:

- increased synthesis of analytical and experimental research
- increased coordination of research projects in the same area
- increased research attention to real problems

With respect to the first, we should try harder to compare our experimental observations with analytical predictions, made in real time during our physical tests. In our actual testing procedures, we should try to compare predicted response with that observed. In this way, we can increase the amount of information gained from each test, and can select our test variables more carefully.

With respect to the second, we should try harder to make our research projects complement rather than duplicate each other. One of the best ways of accomplishing this is through prompt and effective communication of research results

With respect to the last, we should try harder to direct our research attention to problems identified by the profession, rather than at problems we would like to solve. This will increase the benefit to society of our research, and will also increase the possibility of obtaining more research funding from the private sector.

5.3.2 To Develop Alternative Funding Sources for Structural Engineering Testing: There is no doubt that the United States of America has a need for structural engineering testing--structural engineering tasks such as the repair and rehabilitation of our building infrastructure cannot be effectively addressed without continued research. However, it is unlikely that major funding for such research will come from governmental sources.

The United States of America does not at present have the strong Japanese tradition of industrial structural engineering research. This question, and its political implications, are being addressed by the engineering community (Mayes 1990). Development of increased private sector funding for structural engineering research must be our primary goal. Structural engineering researchers in the United States of America must include the following items on their continuing agenda:

- To maintain active contact with practicing engineers and industry
- To actively promote the cost-effectiveness of structural engineering testing
- To actively disseminate their research results to the user community

By pursuing this agenda, structural engineering researchers in the United States of America will help ensure their continued professional usefulness and development.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

In this paper, the objectives of structural testing are summarized as follows:

- to evaluate materials
- to educate engineers, architects, and testing laboratory personnel
- to refine testing equipment
- to evaluate the behavior of mechanical equipment
- to evaluate the behavior of structural elements, subassemblages, or systems
- to demonstrate the validity of a structural design or concept
- to develop and refine analytical models

In the light of those objectives, basic equipment requirements for structural testing laboratories are reviewed, classified as follows:

- transportation equipment
- loading equipment
- data acquisition equipment
- data reduction and reporting equipment

The current state of structural engineering testing practice in the United States of America is discussed in terms of the above objectives and equipment. In particular, the benefits and costs of pseudo-static testing are compared and contrasted with the benefits and costs of shaking table and pseudo-dynamic testing.

6.2 Conclusions

In the United States of America, structural testing practice developed rapidly as a result of strong federal government funding for earthquake engineering research in the 15 years following the 1971 San Fernando Earthquake. One of the landmarks in that development was the series of United States of America - Japan cooperative research programs. As a result of those programs, considerable information has been gained about the relationship between material testing, structural element testing, large-scale building testing, and analytical model development.

In the past 20 years, structural testing in the United States of America has contributed much to our understanding of structural behavior, and has achieved three important qualitative advances:

- o microcomputer technology
- o the shaking table
- o pseudo-dynamic testing

At the same time, continued funding for structural engineering testing is now at a much lower level, in real dollars, than it was 20 years ago. The increased demand for research funding, coupled with decreases in real funding, has created conflicts which are now being experienced throughout the United States of America.

In the United States of America, the pluralism of the political process makes it difficult for the federal government to establish and fund large research centers for structural engineering testing on a long-term basis. It is therefore more probable that testing will continue at a large number of smaller research facilities, and will be primarily pseudo-static rather than shaking-table or pseudo-dynamic. To resolve the conflict between our need for more structural engineering research and our declining federal government budget for such research, the following two general goals must be pursued:

- o more efficiency in pseudo-static structural engineering testing
- o alternative funding sources for structural engineering testing

6.3 Recommendations

Structural engineering researchers are encouraged take the following specific actions:

- o synthesize analytical and experimental research
- o coordinate research projects in the same area
- o pay attention to real problems
- o maintain active contact with practicing engineers and industry
- o actively promote the cost-effectiveness of structural engineering testing
- o actively disseminate their research results to the user community

By pursuing this agenda, structural engineering researchers in the United States of America will help ensure their continued professional usefulness and development.

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