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SUMMARY REPORT OF A WORKSHOP ON RESEARCH NEEDS FOR SHORT-AND MEDIUM-SPAN BRIDGES *

Prepared by the

Industrial Management and Rehabilitation Branch **
Industrial Institutions and Services Division

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** Based on the report of the Proceedings prepared by Computech Engineering Services, Inc., Berkeley, California, USA.

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PREFACE

In November 1986, the National Science Foundation sponsored a Workshop on the identification of long range non-seismic research needs for short- and medium-span bridges. Approximately 35 eminent bridge engineers and researchers attended this workshop from throughout the United States. In addition, representatives from Canada, Latin America and the Caribbean were also in attendance.

State-of-the-art papers were presented in each of the following areas: bridge loads, materials, evaluation and strengthening, management systems, analysis and expert systems. These presentations were followed by workshop group sessions to identify and prioritize long range research needs in each subject area.

These Proceedings review the findings of the Workshop. In total several hundred research needs were identified at the meeting and these are classified and consolidated to just less than one hundred needs. Where appropriate, ranking according to high, medium or low priority is given.

Computech Engineering Services acknowledges the assistance of many people who contributed to the success of the Workshop. Dr. John Scalzi of the National Science Foundation provided valuable advice, support and cooperation throughout the duration of the project. Steering Committee members Bruce Douglas, Gerry Fox, Charles Galambos and Robert Reilly assisted with the development of the Workshop program, helped formulate its objectives and ensured its ultimate success. Special recognition is also made of the Chairmen who led the individual group sessions and compiled the lists of research needs.

At Computech Engineering Services, administrative support for the project was provided by Jennifer Van Heuit, editorial assistance was given by Mary Jacak and word processing/report publication was under the excellent care of Gladys Mui Schwalm.

The participation of experts from Latin America was facilitated by the New York Liaison Office of UNIDO. In particular Robert Hallett, Hassan Bahlouli and Anne Sifuentes organized the attendance of these special visitors. Their particular contribution to the success of the Workshop is also acknowledged.

The material presented in this report is based upon work supported by the National Science Foundation under Grant No. ECE 8520532. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the Workshop participants and do not necessarily reflect the views of the National Science Foundation or Computech Engineering Services, Inc.

1. WORKSHOP OVERVIEW

1.1 Background and Objectives

Bridge building is an art which has been practiced for many thousands of years. Today it has evolved into a complex science as the demand for spanning greater distances increases. The art and science of bridge engineering spans both old and new structures, from early primitive materials to modern high strength steels. Rehabilitating existing structures and designing new bridges that satisfy a multiplicity of design constraints is the challenge facing today's engineer.

To meet this challenge, education, research and innovation are essential, and at least two Federal ag^ncies in the United States (the Federal Highway Administration and the Transportation Research Board) have been active in this area, addressing the immediate (short-term) needs of the bridge profession. It is however necessary that a complementary research effort be directed towards the long-term, ill-defined, high risk/high cost projects to strengthen the present research programs. In recognition of this need, the National Science Foundation sponsored a Workshop in November 1986 to review and identify non-seismic research needs for bridges with special emphasis on long-term needs.

The workshop had the following objectives:

1) To determine the state-of-the-art of bridge design and construction;
2) To identify research needs, currently active research agencies and programs, and opportunities for long-range, high-risk, high-cost research investment; and
3) To identify priorities for these research needs.

Attendance was by invitation only and all participants were requested to suggest research needs in the following areas: materials, evaluation, strengthening, loads, analysis, construction methods, structural form, management and expert systems. Seismic issues were deliberately excluded because of adequate coverage in recent NSF Workshops held elsewhere. Geotechnical topics and hydraulic scour were also consciously omitted from the agenda.

Key personnel from both the private and public sectors participated in this Workshop. These included research and design engineers from Universities, State and Consultant offices. Further, representatives from the Federal Highway Administration (FHWA), the Transportation Research Board (TRB), and the American Association of State Highway and Transportation Officials (AASHTO) were also active participants in this Workshop. Bridge engineers from Latin America and the Caribbean were also in attendance under the sponsorship of the United Nations Industrial Development Organization (UNIDO) and the National Science Foundation.

1.2 UNIDO Contribution

A particular feature of this Workshop was the attendance of 19 bridge engineers from Latin America and the Caribbean. Organized with the cooperation of UNIDO, the following countries were represented: Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Guatemala, Honduras, Panama, Peru, and Uruguay.

Immediately following this Workshop, UNIDO held a second meeting on the Development of Wooden Bridge Construction in Latin America and the Caribbean. U.S. participants were also invited to attend this Workshop which was held from 20 to 21 November at the State Plaza Hotel. UNIDO reports on both meetings have been published under the following titles:

> Report on the Workshop on Development of Wooden Bridge Construction in Latin America and the Caribbean, UNIDO Report IO/R.27, Feb 87.
>
> Technical Report: Bridge Design in the Latin America and Caribbean Region; UNIDO Report IO/R.51, Dec 87.

Both reports are available from the following address:

Chief, Documents Unit
Room F - 355N
United Nations Industrial Development Organization
P.O. Box 300
A-1400 Vienna, AUSTRIA

2. RESEARCH RECOMMENDATIONS

2.1 Workshop Groups

Following two days of keynote lectures and special presentations, working groups met on the third day of the Workshop to discuss and identify research needs. These working groups were as follows:

Bridge Loads:
Professor Andrzej Nowak, University of Michigan (Chairman, Secretary)
U.S. Members: Dorton, Ghosn, Nowak, Reilly
UNIDO Members: Ponce, Rivera, Sollazzo

Bridge Materials:
Dr. John Kulicki, Modjeski and Masters, Pennsylvania (Chairman)
Professor J.K. Rao, California State University, Long Beach (Secretary)
U.S. Members: Albrecht, Gutkowski, Kulicki, Plecnik, Rao, Whiting
UNIDO Members: Mettem, Cano, Castro, deFreitas, Granados, Soreira

Bridge Evaluation and Strengthening:
Professor James Baldwin (Chairman, Secretary)
University of Missouri, Columbia
U.S. Members:
Bakht, Baldwin, Beal, Douglas, Galambos, Klaiber, Leon, Reece, Seim
UNIDO Members: Franco, Lombardo, Tapia, Uriguen, Yi

Bridge Management Systems:
Professor Celal Kostem, Lehigh University (Chairman, Secretary)
U.S. Members:
Friedland, Kostem, McClure, Powell, Sanders, Sutherland
UNIDO Members: Arrango, del Valle

Bridge Analysis:
Professor Frieder Seible (Chairman, Secretary)
University of California, San Diego
U.S. Members: Buckle, Frangopol, Gamble, Roeder, Seible, Scordelis
UNIDO Member: Montero

Bridge Expert Systems:
Professor Celal Kostem, Lehigh University (Chairman, Secretary)
U.S. Members:
Friedland, Kostem, McClure, Powell, Sanders, Sutherland
UNIDO Members: Arango, Del Valle

2.2 Research Recommendations

Several hundred research needs were submitted during the course of this meeting and in the final group sessions these were consolidated to a total of 94. Of these, about one-half were judged to be of high priority. Research needs are summarized below for each subject area noted above. Where appropriate, priorities have been assigned and identified as follows:

H for high priority
M for medium priority
L for low priority

These identifiers are enclosed in parentheses in appropriate subject titles.

It is clear from the following that a large and substantial research effort is required if progress is to be made in the rehabilitation of existing bridges and the design of new bridges. This task is too large and too expensive for any one research agency to undertake on its own. A coordinated effort is required among the active funding agencies and research organizations. Such an effort should be directed by a committee of interested parties (researchers and program directors) with the shared responsibilities of technical direction and optimization of the investment of research funds. Other benefits would include the avoidance of duplicating research effort and the increased opportunity for improved interaction and information transfer with national and international agencies.

Rehabilitation and expansion of the nation's infrastructure is urgent. There is therefore an immediate and obvious need to establish a research program which addresses the problems that are outlined below.

The research recommendations that follow are presented under six headings:

- Bridge Loads
- Bridge Materials
- Bridge Evaluation and Strengthening
- Bridge Management Systems
- Bridge Analysis
- Bridge Expert Systems

A. BRIDGE LOADS

Four subject areas were identified under this general title. These were:

- live loads
- dynamic loads
- other loads
- load and resistance factors/load combinations.

Research needs in each area are listed below:

A1. Live Load

A1.1 (H) Live load model for bridge rating.
Develop live load (truck and/or lane load) for evaluation of existing bridges, to be used by AASHTO. Currently different states use different models.

A1.2 (H) Live load models for bridge design code (new bridges).
Develop live load (truck and/or lane load) to be used for the design of new bridges (AASHTO Specification). Current model (AASHTO) is not adequate.

A1.3 (L) Live load model for transit guideways.
Develop design live load model for future systems to be constructed in the United States. Recently completed transit systems clearly indicate to the need for such models.

A1.4 (M) Histograms of truck weights.
Gather data on truck weights, axle configurations, and axle weights; through truck surveys, weigh-in-motion, and other means.

A1.5 (M) Site-specific load spectra.
Develop live load spectra for typical bridges. Consider interstate highways, state roads, secondary and rural roads, live load spectra for posted bridges. This will serve as a basis to differentiate design criteria. Currently secondary and primary road bridges are designed and evaluated using practically the same criteria.

A1.6 (H) Multiple presence models.
Develop models for headway distance, multiple presence of trucks on multilane bridges (in-lane and side-by-side), load spectra for bridge members (girders) due to multiple presence.

A1.7 (M) Load growth models.
Develop live load models for future bridges, establish load growth rate. This involve truck weight growth, changes in axle configurations, frequency of traffic, multipl presence.

A1.8 (L) Fatigue loading.
Develop load spectra for fatigue analysis, load spectra for members and connections future changes.

A1.9 (M) Bridge load - damage accumulation.
Develop a relationship between live load level and bridge damage accumulatior level, economic analysis (cost) of design, repair, and maintenance as a function of live load level (truck weights, frequencies, axle load and configurations), optimize the bridge formula.

A2. **Dynamic Load**

A2.1 (H) Develop a dynamic load model for design and evaluation of bridges
The following considerations are recommended:

- effect of surface condition (roughness of the road), this is particularly important in short span bridges

- dynamic properties of the bridge (natural frequency of vibration, mass. span, material)

- vehicle properties (suspension system, speed)

- multiple presence, dynamic effect of multiple trucks or axles on the bridges

- live load vs. dynamic load, relationship between extreme live load and dynamic load, dynamic load as a function of truck weight and axle configuration

- dynamic load for timber bridges. In the current AASHTO specifications, no dynamic load is considered for timber bridges. Ministry of Transportation (Ontario) tests indicate there is some dynamic effect. It is necessary to quantify the level of this effect.

- time effect vs. failure mechanism. Investigate the relationship between the truck crossing time and failure mechanism. Failure to timber structures extends in time and a short crossing time may justify higher load.

A3. Other Loads

A3.1 (M) Construction loads.
Develop load models to be used in evaluation of bridges during construction. This particularly applies to segmental bridges, but also to temporary structures (scaffolding, forms)

A3.2 (L) Temperature effects

- Develop temperature effect models for bridges without expansion joints. Elimination of expansion joints helps to reduce deterioration of bridges. However, temperature differentials are the major loading and the current state of knowledge is insufficient.

- Theoretically, nonlinear temperature gradients result in continuity stresses and self-equilibrating stresses. The self-equilibrating stresses acting on an unrestrained structure may produce high stresses within the member which are not clearly understood. Additional physical testing should be conducted to verify the existence and magnitude of these self-equilibrating stresses.

- More field testing is needed to calibrate the proposed temperature differentials for the United States.

A3.3 (L) Collision forces.
More data is needed to develop design criteria for collision forces. In particular the following should be considered:

- vehicle collision (pier, superstructure, railing)
- ship collision
- railway loads (derailing forces, direct impact)

A3.4 (L) Scour
Scouring is identified as the most frequent cause of bridge failure. More research effort should be directed to this problem to determine the effect of scouring on bridge performance, control of damage and prevention.

A3.5 (L) Impact load for bridge railing systems.
Develop design criteria for bridge railing systems.

A3.6 (L) Effects of severe environments on the safety of bridges.
Explore the effects of severe environments such as cold and moisture on bridge performance.

A3.7 (L) Braking forces.
Develop design criteria for braking forces due to single and multiple trucks.

A4. Load and Resistance Factors and Load Combinations

A4.1 (H) Load and resistance factors for the design of new bridges.
Develop load and resistance factors using state-of-the-art methodology in bridg engineering, structural analysis and probabilistic methods.

A4.2 (H) Load and resistance factors for evaluation of existing bridges.
Develop load and resistance factors using state-of-the-art methodology.

Other topics, which are related to A4.1 and A4.2 above, are listed below.

A4.3 (L) Verification of stochastic models.
New methods are now available which have been developed for either buildin structures or in other areas of engineering. They require verification and adjustme to bridge engineering applications.

A4.4 (M) Load combinations for calibration
Develop practical load combinations to be used in the development of load ar resistance factors.

A4.5 (H) Target reliability level(s)
Establish the acceptable safety level(s) for bridges, taking into account age, type, cos and other parameters. This effort must involve a wide spectrum of bridge enginee representing bridge authorities, designers, researchers and users.

A4.6 (M) Reliability models for bridge structures
Develop reliability models for bridge structures using state-of-the-art methodolog Consideration should be given to members as well as structural systems (syste reliability).

B. BRIDGE MATERIALS

Six basic issues and generic research areas were identified by the Materials Group. Concern was expressed that about half of the bridges in the country are in various stages of deterioration. The urgent need for materials research which was oriented towards application in the infrastructure field, was highlighted. Enthusiastic support was given to the concept of national centers of expertise and excellence which would supplement existing materials science groups/centers. The focus of these new centers should be on infrastructure research such as

1. Durability of Construction Materials in Bridges and Infrastructure Rehabilitation

2. Assessn ent Techniques for Construction Materials (includes nondestructive techniques using technology from aerospace, physics and other noncivil engineering fields)

Other topics such as structural adhesives (from the aerospace field), and evaluation of material properties for existing structures were discussed. To encourage new materials, such as composites, it was felt necessary to research the area of consistent safety factor design of bridge components which are made of composite materials to include variations in material properties and load effects.

The six subject areas idenfitied by the Materials Group were:

- mechanical properties
- damage and damage mechanisms
- new and advanced materials
- nondestructive evaluation
- reconstitution
- other topics.

Research needs in each area are listed below.

B1. Mechanical Properties

B1.1 (H) Materials and components (members) and connections

The following should be investigated:

- Environmental exposure effects

- Loading rate effects on material resistance

- In-situ measurement of properties
- Formulation of constitutive equations
- Failure criteria (response to stress fields across the section of members)
- Environmental fracture criteria (stress intensity in flawed/cracked regions) for propagation and energy absorption. Brittle-ductile fracture transitions.
- Long-term time-dependent properties
- Material variability characteristics quantification methodology in a uniform format between materials for characterization of resistance safety factors.

B2. Damage and Damage Mechanisms

B2.1 (H) Accumulation and Control Methods

To avoid or replace corroded metal members or components, the following should be investigated:

- Fatigue control and evaluation of remaining useful service life; prediction methods as a part of rehabilitation and replacement programs in bridge management systems. (For example, steel and composite members.)
- Environmental effects on materials (deicing salts on concrete, decks with protective mechanisms, acid rain, abrasion of wind and particles, biological attack).
- Relationship to serviceability (useability, reliability vis-a-vis repair mechanisms), ultimate strength (especially connections of metal structures, composite materials, members and connections)

B3. New Advanced Materials

New materials requiring application-related study include: fiber-reinforced, composite materials, structural adhesives, and joining techniques for steel. The following topics are therefore recommended:

B3.1 (H) Basic Research into New Materials

- Basic research to develop composite materials in bridge components and connections.

- Structural properties and behavior
- Non-structural issues (Fabrication Technology)
- Cost-effectiveness methodology, with life-cycle economics for load, environmental and durability effects
- Consistent safety factor design of bridge components made of composite materials for variation in material properties and load effects, to give consistent safety levels for bridge strength and serviceability, for corrosion resistance and fatigue.

B3.2 (H) Interaction with Conventional Materials

- FRP connections for metals and wood,
- cover plating

B3.3 (H) Methods to Maximize Structural Benefits

High-strength/lightweight materials should be studied together with the environmental benefits of composites.

B4. Non-destructive Evaluation

B4.1 (H) Material Assessment Techniques (MAT)

- Stress Analysis incorporating MAT output
- Survey of non-related technological fields for possible new material assessment techniques

B5. Reconstitution

B5.1 (H) Basic Materials Studies

- Dispersion of properties and flaws by processing
- Fundamental modification to new form, shape, and on predetermined residual state (autostress, post-tensioning, strengthening)
- Combination of materials
- In-situ modification of structural components

B6. Other Topics

B6.1 (M) Establish databases for correlation of in-situ field performance against laboratory test results.

B6.2 (M) Connection details (linked with B1. and B2.).

B6.3 (M) Characterization of resistance (as related to consistent safety), especially for new materials, composites, structural adhesives (linked with B1.).

B6.4 (M) Process control (linked with others).

C. BRIDGE EVALUATION AND STRENGTHENING

Most of the members of the Evaluation/Strengthening Group are actively involved with short term immediate research needs such as that supported by the NCHRP and the FHWA. All agreed that the more fundamental long range research suggested for NSF support was sorely needed. Accordingly, the Evaluation/Strengthening Group identified the following five general areas of needed research.

- improved rating methods using nondestructive methods
- estimation of load capacity
- correlation of the rate of deterioration with service conditions
- methods of repair, rehabilitation and strengthening
- nondestructive instrumentation.

Research needs in each area are described below.

C1. (H) Implementation of Non Destructive Field Test Results in the Evaluation and Rating Process

Field tests have shown that the "real" load carrying capacity of a bridge is almost always much greater than that predicted by conventional evaluation analyses. This discrepancy is due in large part to conservative modeling assumptions concerning unknown conditions. Non destructive field tests permit many of these assumptions to be eliminated, because the bridge itself provides an exact model. There is a need for more knowledge concerning appropriate measurements and interpretation of the results. Is it possible to identify the critical failure mode? What limit state should be considered in old bridges, yielding or collapse? Once the strength has been determined, what are the appropriate load factors for rating?

C2. (H) Development of a Better Fundamental Understanding of the Real Load-Carrying Capacities of Bridges, using Results of Destructive Field Tests and Analysis

If the differences between "real" and predicted ultimate strengths are as great as some field tests indicate, a great deal more knowledge is needed concerning modeling and analytical procedures. Test data on a wide variety of bridges are needed as a check on improved procedures as they are developed. Perhaps a center for bridge testing is needed. Such a center might serve as a clearing house for information on bridges that become available for testing, a repository for bridge test data, and a source of advice on what test information is needed. Such a center might also provide partial support for field tests and as a stimulus for sponsorship by other entities.

C3. (H) Correlation of Deterioration Rates with Service Loads and Conditions

It may be that far too much emphasis is being placed on evaluation of the current ultimate strength. In rating a bridge, what is really needed is a prediction of both the strength and serviceability of the bridge just before the next inspection. This obviously requires some prediction of deterioration under future service conditions. Except for fatigue, very little is known about deterioration rates of bridges under service conditions.

It may become possible to substantially increase estimates of current ultimate strength through incorporation of field test data in the evaluation process. If such a development were to result in substantially increased service loads, accompanying increases in deterioration rates would undoubtedly nullify at least part of the apparent gain.

C4. (M) Repair, Rehabilitation and Strengthening

If an old bridge is evaluated and found to be unsuitable in its existing condition to carry the traffic for which it is needed, decisions must be made concerning possible repair, rehabilitation, strengthening or replacement. Research is currently being conducted under several TRB projects in an effort to bring together available knowledge on techniques for accomplishing each of these. However, there is still a need for overall design criteria to be applied when working with old bridges. Since old bridges may not be expected to last as long as a new bridge, the design criteria for repair, rehabilitation and strengthening may not be the same as those for new bridges.

C5. (M) Development of New Non-Destructive Instrumentation for Field Testing and Instrumentation

Experimental measurements are always limited to some extent by the available instrumentation. Development of new instruments which are more economical, easier to use, more reliable, more precise, and would measure additional parameters, would be quite helpful in the evaluation process. Crack detection, measurement of corrosion deterioration and in-situ measurement of material properties such as fracture toughness are suggested for consideration.

D. BRIDGE MANAGEMENT SYSTEMS

Research needs in bridge management systems (BMS) are divided into two major categories:

- BMS programming
- Strategic long range planning

"BMS programming" is not limited to "computer programming" per se. The research recommended within this category includes both fundamental and applied research. The nature of the end product of BMS will inevitably be computer-based software systems, databases, and rules and guidelines. Within "BMS programming" the major subject headings for recommended research programs include:

- Optimization models for BMS
- Rating and Routing via BMS
- Decision-making strategy and activity effectiveness.

Research needs in these areas are listed below.

D1. BMS Programming

D1.1 Optimization Models

Mathematical optimization models should be formulated and implemented in the prioritization and selection procedures.

Models such as the linear programming procedure and the stochastic decision process should be formulated for use in the prioritization and selection procedure of an effective bridge management system. Models with funding constraints generally contain decision-making features and become quite complex but should be computationally feasible. The optimization models should be developed for implementation as the basic data quality and quantity increase during the later stages of bridge management development.

D1.2 Rating and Routing

Procedures must be developed to enable the state transportation departments to regulate the weights of licensed vehicles that can use the bridges and also to assess the bridges for safe passage of overweight vehicles operating with special hauling permits.

D1.3 Decision strategy and activity effectiveness

- Analytical tools are needed to accurately determine the reponse characteristics of repaired, retrofitted, or strengthened bridge structures.
- The feasibility of improved cost effective techniques for erecting, maintaining, repairing, testing and strengthening of bridges needs to be investigated.
- Collection and interpretation of data on the effects of specific maintenance, repair and rehabilitation on bridge performance is needed.
- The effect of maintenance, rehabilitation and replacement activities on bridge life must be determined.
- Determination of the cost-effectiveness of bridge maintenance, rehabilitation, and replacement.
- Development of benefit-cost analyses to determine bridge activity costs and user costs.

The feasibility of improved cost effective techniques for inspecting, posting, testing, maintaining, repairing, and replacing bridges must be explored. Effective bridge management requires reliable information on the additional service life that can be purchased with discretionary expenditures on existing bridges. Life-cycle costing using accurate data should be used to determine the optimum amount of funds to be spent on bridge activities. A systematic plan for collection of data on the effects of various bridge activities could be carried out at an NSF "Center of Excellence."

D2. Strategic Long Range Planning

D2.1 Develop accurate methods to predict future needs.

Since 1970, $12 billion in Federal funding has been made available to States and local governments to improve bridges. Despite these unprecedented expenditures, 41 percent of the Nation's 574,000 highway bridges remain deficient. Each year as many bridges are added to the national list of deficient bridges as are removed from it. For the present, bridges are maintaining the status quo. However, because 40 percent of all existing highway bridges are between 15 and 35 years old, bridge needs are likely to increase substantially in the next two decades. Because current projections indicate a probable increase in the rate of bridge need growth, a comprehensive system is needed which will anticipate future needs and respond to changes in funding levels. The greatest potential benefits of a comprehensive bridge management system are the ability to explore a wide range of "what if" questions and predict what is going to happen in the future.

E. BRIDGE ANALYSIS

The identification of research needs in the bridge analysis area is complicated by the fact that all bridge research areas have some kind of analytical component. This makes it difficult to separate out individual analytical needs without direct reference to the overall research needs.

Therefore an attempt is made to identify analytical research needs by application rather than by more traditional methods in order to establish a clear objective.

A total of six application categories were identified as follows:

- Analytical Tools for Limit State Design
- Analytical Tools to Assess the Effects of Structural Rehabilitation
- Time History Models
- Systems Identification Methods
- Experimental Verification Analytical Models
- Special Topics

In addition to the identification of individual research needs within the above categories, the following general concerns are expressed regarding the development of new complex analytical tools:

a) There exists a large gap between the state-of-the-art in bridge analysis and the analytical tools most frequently employed in the practicing engineering community. Every effort should be made to disseminate advances in the analytical field in order to overcome the "recipe" oriented bridge design approach.

b) The analysis of a bridge structure is only as good as the model used to represent the actual conditions. Frequently obtained large discrepancies between analytical predictions and field load test results are often attributed to inadequate analytical methods whereas in fact the modelling of boundary conditions and secondary effects is in error.

c) Complex analytical methods have to be validated by experimental verification tests. In the nonlinear and failure range, large- or full-scale experimental models are needed to properly identify prototype behavior. Analytical models have to be calibrated against experimental tests under controlled laboratory conditions first before any reliable field applications can be made. The importance of, and necessity for, experimental validation of analytical models prompted the listing of a separate research category in that area even though experimental testing was not explicitly addressed in this workshop.

E1. Analytical Tools for Limit State Design

With worldwide changes in bridge design philosophy towards Limit State Design concepts, analytical tools have to be developed which address the individual limit states for the local (e.g. anchorage details), regional (e.g. transverse bending) and global (e.g. overall behavior) design of the bridge structure.

E1.1 (L) Service Limit State

Develop linear elastic models which can predict deflections and service stress levels.

E1.2 (H) Overload Limit State

Develop nonlinear models (cracking, yielding, etc.) which can trace the post-working stress behavior for Special Permit Overloads

E1.3 (H) Ultimate Limit State

Develop nonlinear modesl which can trace the complete behavior up to failure, including force redistributions, in redundant systems and simplified models which can easily evaluate possible collapse and failure mechanisms

E2. Analytical Tools to Assess the Effects of Structural Rehabilitation

With the volume of necessary structural rehabilitation of the national bridge inventory increasing, analytical tools have to be developed which can accurately predict the current state of existing bridge structures and allow the implementation of repair and strengthening measures in the modelling.

E2.1 (H) Assessment of Damaged and/or Existing Structural State

Develop models in which damage can be introduced and the effectiveness of repair studied

E2.2 (H) Models for Repair and Strengthening Methods

Develop models in which the addition of external tendons, composite overlays, and the like can be studied

E3. Time History Models

Accurate models are needed which can represent construction stages and associated force redistributions, environmental effects, time-dependent effects and load histories for arbitrary bridge geometry.

E3.1 (H) Dynamic Amplification Load Allowance: impact and braking.

E3.2 (H) Construction Sequences: segmental.

E3.3 (H) Environmental Loading: temperature, wind.

E3.4 (H) Long Term Effects: prestress losses, creep, shrinkage, corrosion.

E4. System Identification Methods

To facilitate dissemination of analytical tools and enhance application, black box models need to be developed.

E4.1 (M) State and Capacity Determination of Existing and/or Damaged Bridges

Develop models based on design and field data input, include non-structural components and effects.

E4.2 (H) Determination of Dynamic Response

Develop methods for parameter identification, and response spectra for traffic loads.

E4.3 (M) Analytical Tools for Hazard Scenarios

Establish the effects of a series of events, and how they impact on bridge safety.

E5. Experimental Verification of Analytical Models

The high costs associated with large-scale experimental testing precludes large-scale experimental parameter studies. However, these parameter studies can be carried out with analytical models as long as they are properly validated by experimental data.

E5.1 (H) Large-Scale Testing in Controlled Laboratory Environments

Carefully planned laboratory tests are needed for verification and calibration of analytical models.

E5.2 (M) Field Testing

After the appropriate laboratory verification, complex analytical models should be applied to field tests.

E5.3 (M) On-line Testing Procedures

Analytical tools for interactive testing, substructuring must be developed

E6. Special Topics

This special topics category contains all suggested research needs not covered in other application areas.

E6.1 (L) Timber Bridge Analysis Problems

E6.2 (M) Falsework, Fabrication and Erection Stages

E6.3 (H) Pre- and Post- Processing Software: interactive graphics systems, and the like.

F. BRIDGE EXPERT SYSTEMS

The research needs in the area of "expert systems," using the broadest definition of the term, can be categorized under two major headings:

- **Computer-aided design, manufacturing, and information exchange, and**
- **Application of expert system technology in planning, design, construction, maintenance, inspection and rating.**

The research activities that need to be carried out under the above-defined general categories are described below.

F1. Computer-aided design, manufacturing, and information exchange:

F1.1 Determine the components of an expert system in bridge design

A critical review of the current and projected capabilities of expert system technology should be undertaken. Similarly, various types of activities carried out in the bridge design process should be identified. Prototype models and expert systems should be developed to execute these activities to demonstrate and verify the practicality of the approach.

F1.2 Extend expert systems into manufacturing process.

It is believed that manufacturing aspects of "bridge engineering" need to be upgraded urgently. The feasibility of the use of expert systems for this process needs to be identified and demonstrated.

F1.3 Develop a "common information exchange 'format'".

A short term solution to developing integrated software systems is to design a universally accepted information exchange format. The "format" should be general, flexible, compact, simple, expandable and "politically acceptable." The format should cover all aspects of bridge engineering, and should be human-readable as well as machine-readable.

F1.4 Software integration through "shared" data and common "architecture"

A truly integrated software system will not merely exchange data among programs, but will operate from a common database. The integrated software should also have a common architecture for all applications. Furthermore, it should be possible to configure the system to reflect regional differences in design styles, and to change it easily to reflect the changes in design codes. Fundamental research is needed to identify appropriate tools and techniques to perform the above missions. Even though the developments in expert systems have not reached full maturity, as compared to, for example, the finite element method, there are still plenty of "tools" at this time that can be expeditiously applied in a "production environment."

F2. Application of Expert System Technology

F2.1 Development of expert systems to be used as a "training guide and surrogate consultant" on the analytical modeling and analysis of bridge superstructures.

Recent developments in the analytical modeling of bridge superstructures have become quite sophisticated. Some of the state-of-the-art tools are too complicated to be digested and used by "average" bridge engineers within the limited time at their disposal. The systems to be developed can be used both as a teaching/training aid and as an advisory tool to be referred to in the production mode.

F2.2 Development of expert systems to be used in construction, quality assurance and quality control, and in the assessment of reliability of "data."

A number of issues frequently encountered in bridge engineering can best be handled via expert systems yet to be developed. The issues which need to be addressed include, but are not limited to: How to relate quality assurance to structural reliability?, Sensitivity analysis as applied to bridge engineering and identification of the parameters most vulnerable to human errors, and development of error control strategies.

F2.3 Development of expert systems to optimize bridge inspection intervals

Evaluate and, if possible, revise inspection intervals based on the observed deterioration rate and the consequences of local failure and deterioration for each structure type.

F2.4 Development of expert systems for the quantification of inspection reports

Expert systems provide a means of capturing the knowledge of skilled employees in transforming qualitative inspection reports to quantitative assessments of strength.

F2.5 Development of expert systems to be used in conjunction with "bridge management systems."

Bridge management system' (BMS) require the implementation and interfacing of expert system concepts. This application will permit the uniform application and interpretation of BMS results and findings. Without such application, there exists the probability to make accidental and/or systematic errors.

F2.6 Application of "empty expert system shells" to bridge design, analysis, construction, rating, inspection, and maintenance.

A number of empty expert system shells are available. It is highly desirable to study the feasibility of using these existing systems in bridge engineering. If this feasibility can be successfully demonstrated, possible major investments in the development of expert systems can be substantially reduced and the implementation of the projects can be expedited.

3. WELCOME AND INTRODUCTORY REMARKS

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Thank you very much for the opportunity to welcome you here this morning to this Workshop. As sponsor of this meeting, my colleagues at the National Science Foundation and I are particularly interested in the outcome of your discussion.

We of course, are looking forward to the research needs that will be identified during the Group Meetings later in the week, and the formulation of a Research Agenda. In the meantime, and to help set the stage for your deliberations, I would like to overview the current bridge research program at NSF.

3.1 OVERVIEW OF BRIDGE RESEARCH PROGRAM

In a recent re-organization of the Directorate for Engineering at The National Science Foundation, several divisions, and programs were established with new responsibilities in order to enable the Foundation to meet the current and future challenges which have developed in our society.

The goals of the Engineering Directorate have been set forth in four statements, as follows:

1. Insure that the United States is at the leading edge of engineering research in all fields.

2. Assist U.S. engineering schools in reproducing the world's best engineers.

3. Find ways for the U.S. to benefit from the full research potential of universities, colleges, industry and government resources.

4. Insure that sufficient fundamental knowledge and experties is available along with cross-disciplinary activities, to stimulate advances in engineering in the private sector.

3.2 STATE-OF-THE-ART: WORLD SCENE
Bridge Engineering - An International Perspective

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In the more highly developed countries of the world, many bridge engineering concerns are similar. For short and medium span bridges, the major concerns of the practicing bridge engineer can be placed in the following six categories:

- Design code philosophies
- Safety and probabilistic methods
- Definition of loads
- Analytical methods
- Contract and construction practices
- Bridge management

In this presentation the international situation is reviewed in each category, covering such items as limit states design, increasing code complexity, structural safety levels, vehicle weight control, collision loads, inelastic methods of analysis, bridge system behavior, construction safety, serviceability concerns, design life, and criteria for rehabilitation.

Goals are then set in each of these six categories for a 10 to 15 year time frame, and detailed research and development needs are identified so as to reach these long-term goals.

These technical needs must also include certain non-technical developments which are affecting structural engineering today. These are discussed under the headings of engineering control, expert systems, liability issues, and innovation.

BRIDGE ENGINEERING

AN INTERNATIONAL PERSPECTIVE

1. Introduction
2. Concerns
3. Present Situation and Goals for 10 - 15 Years Hence
4. Professional or Social Aspects
5. Concluding Remarks

2. CONCERNS

A. Design Code Philosophies

B. Safety and Probabilistic Methods

C. Definition of Loads

D. Analytical Methods

E. Contract & Construction Practices

F. Bridge Management

3A. DESIGN CODE PHILOSOPHIES (Present Situation)

- Design Approach in State of Change
- WSD - LFD - LRFD - LSD
- Varied Degrees of Calibration
- Concern About Greater Complexity and Length
- Longer Time to Design Simple Bridges
- Non-uniform Terminology, LF and ϕ Factors
- Global and Partial S.F. Approaches
- Compare Europe, North America and Other Countries
- More Items Covered in Codes by Request
- Codes Tending to Become "Recipe" Books
- Unified Codes - Eurocodes or Specialty Codes?

3A. DESIGN CODE PHILOSOPHIES (Future Goals)

- All Codes in Calibrated LSD Format
- Equal Concern for SLS and ULS
- Simpler to Apply - 2 Level Format
- Common Terminology
- Common Approach for All Structural Design Codes
- Foundation & Soils Interaction in Same Format
- Consistent Coverage for Concrete
- To Cover New Designs, Evaluation & Rehabilitation Designs
- Code Clauses to Better Reflect Bridge Testing Results
- Code Philosophy Clear and Well Understood by Users

3B. SAFETY & PROBABILISTIC METHODS (Present Situation)

- WSD Simple but Safety Level Uncertain
- Target Safety Levels for LSD Arbitrary
- Public Acceptance of Failure Frequency Not Clear
- Safety Level Based on Lifetime Costs
- Concern About Human or Gross Errors
- Design Life Concepts
- Calibration Needed for Load Combinations other than DL + LL + I
- Single Load Path - Definition
- Calibration for SLS Minimal
- Soil/Structure Interaction
- Failure from Flood & Scour
- Data Base for Probabilisitic Methods

3B. SAFETY & PROBABILISTIC METHODS (Future Goals)

- Agreed Safety Levels for ULS Design Based on Public Acceptance of Risk
- Human Errors Reduced by Improved Checking and Control Procedures
- Design Life Established, Based on Material and Environmental Data
- Codes Calibrated to Agreed Safety Level & Various Target Design Lives
- Codes Calibrated for All Load Combinations at ULS and SLS
- Single & Multiple Load Path Bridge Types Clearly Defined
- Improved Data for Probabilistic Methods Based on Performance Measurements

3C. DEFINITION OF LOADS (Present Situation)

- Increase in Vehicle Weights
- Lack of Effective Weight Control
- Susceptibility of Short Spans to Overloads
- Multiple Presence, Multi Lane Loads
- Live Load Dynamic Effects, Including Multiple Loads
- Accuracy of Live Load Models for Design and Evaluation
- Temperature Effects - Gradient Model, Integral Abutments
- Collision Loads - Roadway and Rail Vehicles and Ships
- Relationship Between Legal Weights, Enforcement, Actual Weights, Design Models, Damage and Economics

3C. DEFINITION OF LOADS (Future Goals)

- Improved Vehicle Weight Control
- Representative Design Model from Load Surveys and Sensors
- Better Method for Dynamic Load Description - Keep Simple
- Greater Use and Understanding of Integral Abutment Bridges
- Realistic Definition of Likely Collision Loads
- Establish Rational Relationship Between Loads and Damage

3D. ANALYTICAL METHODS (Present Situation)

- Little Advantage in Further Complexity in Analysis
- Elastic Methods Still Used at ULS
- Available Plastic Redistribution Methods Not Suitable for Designers
- Designing for Component Behavior
- Analytical Results Often in Disagreement with Load Test Data
- Methods Not Always Suited to Evaluation of Deteriorated Bridges

3D. ANALYTICAL METHODS (Future Goals)

- Plastic Redistribution Methods Available for ULS Design
- Analysis of Whole Structure Possible Instead of Components
- Analytical Methods in Agreement with Full Scale Test Results
- Effects of Deterioration (e.g. Concrete Cracking) Incorporated into Evaluation Analytical Methods
- Improved Modelling and Analysis of Soil/Structure Interaction

3E. CONTRACT & CONSTRUCTION PRACTICES (Present Situation)

- Changing Contracting Methods Makes Overall Responsibility Less Clear
- Increased Use of Computer Drafting
- Problems of Data Transfer and Compatibility of Micros
- Responsibility for Falsework and Other Temporary Works
- Construction Loads and Safety Levels
- On Site Safety - Responsibility

3E. CONTRACT & CONSTRUCTION PRACTICES (Future Goals)

- Standard CADD Methods for Contract Preparation
- Easy Data Transfer by Micros
- Standard Details by Graphics to Simplify Construction
- Improved Knowledge and Standards for Construction Safety Levels
- More International Construction Specifications - Performance Specifications
- Clear Definition of Responsibility for On-Site Safety

3F. BRIDGE MANAGEMENT (Present Situation)

- New Methods Being Developed
- Inspection and Evaluation Methods Vary and Often Inadequate
- Serviceability Concerns Now on 1960's Designs for Minimum Material
- Loss of Durability with Time Not Well Understood
- Hard to Estimate Remaining Life
- Lack Rehabilitation Design Criteria
- Need a Decision Model for Rehabilitation
- Repair Problems with Urban Elevated Expressways
- Heritage Bridge Rehabilitation Methods

3F. BRIDGE MANAGEMENT (Future Goals)

- New Non-Destructive Condition Survey Methods
- Repair Methods for PSC Bridges
- Methods to Predict Rate of Deterioration and Future Life
- Rehabilitation Design Code
- Decision Model to Establish Best Time to Carry Out Rehabilitation
- Methodology to Set Rehabilitation Priorities for Bridge Networks
- Maintenance Handbook Applied to Ensure Design Life Met

4. PROFESSIONAL OR SOCIAL ASPECTS

Areas of general concern to be considered in research and development needs.

1. Engineering Control
2. Expert Systems & Artificial Intelligence
3. Liability Issues
4. Innovation

4.1 ENGINEERING CONTROL

- Perceived Loss of Control with CADD Systems, Comprehensive Standards and Codes
- No Longer One Person in Charge
- Need to Keep, and Ability to Question, Computer Output
- Design Initiative Tends to be Stifled by the System

4.2 EXPERT SYSTEMS & ARTIFICIAL INTELLIGENCE

- Suited to Diagnosis & Rehabilitation
- Threat or Opportunity for Structural Engineers?
- Development by Structural Engineers or Computer Experts?
- Potential for Profound Changes in Engineering Work & Education

4.3 LIABILITY ISSUES

- With Increase in Claims and Litigation, No Incentive to Take Risks
- On-Site Responsibility Often Unclear and Produces Move Towards Reduced Involvement
- Liability Risks Extending to New Areas - Code Writing, Railings

4.4 INNOVATION

- Most Research is Contract Type
- Need Speculative Research Opportunities Also
- Individual Initiatives Could be of Significance - Examples

3.3 STATE-OF-THE-ART: TIMBER AS A BRIDGE MATERIAL

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OVERVIEW

Important needed developments are as follows:

- Development of a timber railing design which meets the vehicle impact requirements of AASHTO
- Development of AASHTO bridge standards specific to bridges on low-volume roads
- Synthesized information on the design, construction, rehabilitation, and economics of timber bridges
- Increased education on wood as a structural material and experience with timber bridges on the part of bridge engineers
- Documentation of the initial in-place cost and eventual life cycle economy of timber bridges compared to bridges comprised of other materials.
- More flexible Federal highway funding for bridge projects vis-a-vis satisfaction of AASHTO requirements
- Development of comprehensive standard timber bridge plans to help reduce local engineering costs.

RESEARCH NEEDS

Loadings

- Dynamic excitation due to moving loads
- Data on contemporary off-system bridge loadings
- Design for loadings in excess of HS20
- Field tests under moving repeated loadings
- Determination of appropriate impact loads for bridge railing systems.

Structural Analysis

- Development of rigorous analytical models to predict the real behavior of timber structural systems. Such models would recognize orthotropic material properties and their variability, load sharing, component interaction, and complexities such as discontinuities, semi-rigid connections and their nonlinearities.
- Analytical studies of horizontal and torsional shear stress distributions acting independently or in combination
- Development of an improved failure criterion
- Methodology for predicting torsional buckling capacity
- Rigoruous evaluation of horizontal shear stress at interior supports of cantilever/continuous members
- Development of theoretical procedures which readily incorporate duration of load data into reliability-based design procedures for heavy timber structural systems and members.

Experimentation and Product Development

- Short and long-term performance of connections under static and dynamic loading
- Need for statistical data base for strength properties

- Effects of cuts, notches and holes on strength and stiffness of wood members
- Effect of preservative treatments on strength after wetting and drying cycles
- Studies of effectiveness of various methods of interconnecting glulam bridge decks a: ' steel stringers
- Development of more efficient glulam beam sections such as I, H and box shapes
- Post tensioning of mechanically laminated bridge decks to increase stiffness and load sharing characteristics
- Development of effective wood/steel and wood/concrete composites
- Fatigue strength of connections
- Studies of the use of hardwood laminations
- Implementation of laminated veneer lumber as tension laminating material in glulam beams.

In-Place Performance

- Development of procedures to determine capacity of existing timber structures
- Research related to the methods of field repair for deteriorated or damaged structures
- Field monitoring of performance of long span timber structures
- Controlled field study of moisture content history of large timbers in exposed environments
- Effects of field expedients and modifications on calculated performance
- Study of tolerance of asphaltic wearing surfaces for relative motion (horizontal and vertical) or deck panels
- Development of effective preservative treatment for in the field e.g. for treating drilled holes, arresting decay.

Design

- Development of moment connections for rigid frame designs
- Development of design procedure for longitudinal bridge deck systems
- Methods for the design of timber guardrails in accordance with AASHTO criteria
- Conversion to a reliability based limit states design code methodology
- Criteria for eliminating cracking of asphalt atop timber decks
- Alternatives to solid sawn bridge curbs and rails to minimize or eliminate seasoning checking
- Criteria for determining the size and spacing of intermediate lateral supports for heavy timbers.

3.4 STATE-OF-THE-ART: CONSTRUCTION METHODS - A CASE STUDY
The UNIDO Prefabricated Modular Wooden Bridge

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The United Nations Industrial Development Organization (UNIDO) has developed, through a project in Kenya financed by the United Nations Development Programme (UNDP), a unique bridge system suitable for developing countries with or without forest resources. The bridges can span up to 30 metres (longer bridges with multiple spans are possible) and carry up to 40 tonnes live load and are therefore most suitable for secondary and access roads. The bridges are fully engineered; the cost is estimated to be less than one-half that of reinforced-concrete bridges.

The basic element is a triangular, 3-metre long timber panel with mild-steel plates pinned and spot-welded at the joints. It weighs 150-200 kg depending on the materials used. Prior to leaving the workshop for the bridge site, all panels are loaded in pairs using a hydraulic jack to ensure that they meet design specifications.

Other advantages are that the standardized components (3-metre wide, fully engineered wooden triangular panels and 3.1-metre steel tension chords), do away with the need for expensive and, in some developing countries, scarce engineering design for each bridge. The components can be made in small workshops, transported without heavy lifting equipment and, once the abutments are built, erected in a few days using various tripod, cable and winch arrangements. The expected lifetime of the bridge is between 15 and 25 years.

Pairs of panels are assembled into cross-braced trusses and launched by various means across the river. With the wet-crossing method two tripods are used, while with the stream-bed method, the elements are lifeted into position and held with a scaffolding until the span is completed. The ends of the first and last panels are fixed to the abutments with a bearing plate. The panels are always launched in pairs, and each pair of panels is cross braced. After the truss has been fixed, diagonal bracing is added.

The bridge deck is then nailed onto the trusses, and the handrails are fitted.

Almost any species of timber may be used, provided the timber is selected for quality and its strength is sufficient. Preservative treatment is necessary if the species is not naturally resistant to biogradation. Mild-steel plates, flats and rods are used, plus nails and bolts which should be galvanized for bridges in tropical areas. Normally, cement and reinforcing rods are used for abutments; however, development on the use of timber for abutments, approaches (cribwork) and tension chords, which are normally of mild steel, is under way.

Strict quality control, test loading of each panel and attention to detail are necessary for safety and to avoid problems in erection. The training of workshop and site crews is straightforward. Various options exist for the manufacture of components: they can be subcontracted to specialized workshops or made entirely in a bridge workshop that has woodworking and metalworking facilities.

The costs will vary from country to country and depend on the source of supply (imported or domestic) and the size of the order.

Annex 1

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November, 1986

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