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REPORT

Reliability of Containment and Safety-Related Structures

by

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RELIABILITY OF CONTAINMENT AND SAFETY-RELATED STRUCTURES

A report prepared by M.A. Nessim, Centre for Engineering Research, under contract to the Atomic Energy Control Board.

ABSTRACT

A research program on Reliability of Containment and Safety-related Structures has been developed and is described in this document. This program is designed to support AECB's regulatory activities aimed at ensuring the safety of these structures. These activities include evaluating submissions by operators and requesting special assessments when necessary. The results of the proposed research will also be useful in revising and enhancing the CSA design standards for containment and safety-related structures.

The process of developing the research program started with an information collection and review phase. The sources of information included C-FER's previous work in the area, various recent research publications, regulatory documents and relevant design standards, and a detailed discussion with AECB staff. The second step was to outline the process of reliability evaluation, and identify the required models and parameters. Comparison between the required and available information was used to identify gaps in the state-of-the-art, and the research program was designed to fill these gaps.

The program is organized in four major topics, namely: development of an approach for reliability analysis; compilation and development of the required analysis tools; application to specific problems related to design, assessment, maintenance and testing of structures; and testing and validation. It is suggested that the program should be supported by an on-going process of communication and consultation between AECB staff and industry experts. This will lend credibility to the results and facilitate their future application.

The projects suggested as part of the research program are intended to address:

- Reliability methodology for assessment of containment and safety-related structures.
- Uncertainties associated with design basis loads such as accident pressures, seismic loads and airplane collisions.
- Validation of simplified structural models as a basis for reliability analysis.
- Shear strength models for reinforced concrete walls for reactor vaults.
- Generic reliability-based design and assessment checks.
- Inspection and maintenance to detect material deterioration.
- Updating reliability based on pressure test results.

For each project, a rationale, objective and preliminary scope have been developed. Based on AECB's priorities and any applicable scope and schedule constraints, the proposed projects can be used as a basis for planning a research program in the area of structural reliability.

RÉSUMÉ

Un programme de recherches portant sur la fiabilité du confinement et sur les structures liées à la sûreté a été élaboré et est décrit dans le présent document. Ce programme est conçu pour soutenir les activités réglementaires visant à assurer la sûreté de ces structures. Ces activités comprennent l'évaluation de soumissions par des opérateurs et les demandes d'évaluations particulières s'il y a lieu. Les résultats de la recherche proposée seront également utiles pour l'examen et l'amélioration des normes de conception de l'ACNOR en matière de confinement et de structures liées à la sûreté.

Le processus d'élaboration du programme de recherches a débuté avec la cueillette de renseignements et la phase d'examen. Les sources de renseignements comprennent les travaux antérieurs du CFER dans ce domaine, diverses publications de recherches récentes, des documents de réglementation et les normes de conception pertinentes, ainsi qu'une discussion détaillée avec les employés de la CCEA. La seconde étape a consisté à établir les grandes lignes du processus d'évaluation de la fiabilité et à définir les modèles et les paramètres requis. On a établi une comparaison entre les renseignements requis et les renseignements que l'on pouvait se procurer pour déterminer les lacunes de la technologie de pointe employée, et le programme de recherches a été conçu de manière à pallier ces lacunes.

Le programme est divisé en quatre sujets principaux, notamment l'élaboration d'une démarche pour l'analyse de la fiabilité, la compilation et l'élaboration des outils requis pour l'analyse, l'application de la démarche à des problèmes particuliers de conception, d'évaluation, d'entretien et d'essai des structures, et finalement les essais et la validation. Il est suggéré d'accompagner le programme d'un processus continu de communication et de consultation entre les employés de la CCEA et les experts de l'industrie. Ainsi, une certaine crédibilité sera accordée aux résultats et à l'application ultérieure de ces derniers.

Les projets proposés dans le cadre du programme traitent des questions suivantes :

- Méthodologie relative à la fiabilité pour l'évaluation des structures de confinement et des structures liées à la sûreté
- Incertitudes liées à la conception des charges fondamentales, comme les pressions en cas d'accident, les charges sismiques et les collisions d'avions
- Validation des modèles structuraux simplifiés à titre de fondement pour l'analyse de fiabilité
- Modèles de résistance au cisaillement pour les parois en béton armé des voûtes de réacteurs
- Vérification générique fondée sur la fiabilité de la conception et de l'évaluation
- Inspection et entretien visant à détecter la détérioration des matériaux

- Mise à jour de la fiabilité fondée sur les résultats des essais de pression.

Pour chacun des projets, la raison d'être, les objectifs visés et la portée préliminaire ont été établis. Fondés sur les priorités de la CCEA et sur toute contrainte relative à la portée ou au calendrier applicable, les projets proposés peuvent être employés pour planifier un programme de recherches dans le domaine de la fiabilité structurale.

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1.0 INTRODUCTION

1.1 Objective

This report is the result of a project carried out for the Atomic Energy Control Board (AECB) to develop a research program on structural reliability of nuclear containment and safety-related structures. The purpose of this research program is to support AECB's activities aimed at ensuring safe operation of these structures.

1.2 Definition of Systems Considered

Containment structures refer to the concrete portions and embedded parts of the containment envelope, which provides a barrier to contain radioactive matter that could be released in case of failure of the fuel cooling system. Reinforced and prestressed (bonded and unbonded) concrete are both used for the construction of containment structures for CANDU reactors. *Safety-related structures* are structures that support, house or protect systems or components that are required for the safe operation and safe shut down of the reactor. The construction materials used for safety-related structures are structural steel, reinforced concrete, and prestressed concrete.

The research program described in this document deals only with containment and safety-related structures. It excludes safety systems and mechanical components forming part of the containment envelope. It must be recognized, however, that some safety systems affect the load applied on containment structures, and therefore a description of the performance of these safety systems is required to evaluate the reliability of containment structures.

1.3 Related Regulatory Regime and Activities

The regulatory document R-7 "Requirements for Containment Systems for CANDU Nuclear Power Plants" adopts a performance-oriented approach to fulfilling its function in ensuring the safety of nuclear facilities in Canada. It sets safety performance standards and requires the operators to demonstrate that their facilities will meet these standards. The AECB ensures that the safety standards are met by reviewing all aspects of a project before a license is granted, and monitoring the operation thereafter to ensure that all safety conditions in the license are met.

The technical areas that must be addressed by AECB in safety evaluations of containment and safety-related structures include:

- Design of new structures.
- Proposed modifications to existing structures.
- Qualification of existing structures for new hazards.
- In-service inspection and maintenance of existing structures.
- Pressure testing of existing structures.

In each of these areas, AECB's role may be to respond to submissions by operators, or to identify potential inadequacies and require the operators to address them.

1.4 Reliability-based Safety Evaluation

Based on current structural design methods, a performance-oriented approach to the safety of containment and safety-related structures can be based on specified minimum reliability levels with respect to the different potential failure modes (*e.g.*, excessive leakage in accident conditions, non-elastic deformations, or section collapse). In this context, reliability is defined as the probability that the structure will sustain, without failure, all the loads to which it is subjected during its design life (*i.e.*, reliability = 1 - probability of failure). Reliability can be assessed directly by carrying out a structural reliability analysis and comparing the calculated reliability levels to the minimum requirements.

Structural reliability can also be ensured by satisfying the requirements of a reliability-based design standard. Such standards, referred to as limit states standards, specify a set of prescriptive design requirements that are defined such that a structure that satisfies them will meet specified target reliability levels. There are a number of such standards for containment and safety-related structures in Canada, which are used as a safety evaluation tool by AECB. The main standards in this regard are CAN/CSA N287.3 (for containment structures) and the draft CAN/CSA-N291 (for safety-related structures), which refer extensively to the provisions of the National Building Code of Canada, and the design codes for concrete buildings (CAN3-A23.3) and steel buildings (CAN/CSA-S16.1). Determination of ground motions and seismic design are addressed in CAN/CSA-N289.2 and CAN/CSA-N289.3.

1.5 Goals of the Research Program

The proposed research program is designed to support AECB's safety evaluations of containment and safety-related structures (as described in Section 1.3). As discussed in Section 1.4, these safety evaluations utilize reliability analyses or reliability-based standards. The goal of the proposed program is therefore to develop a comprehensive methodology that can be used to assess the reliability of containment and safety-related structures under all conditions that may be encountered during their service life. The results will be directly applicable to safety evaluation. They will also provide a basis for evaluating, revising and updating the relevant design standards. The outcome will be a more consistent set of standards that can be utilized more confidently in safety evaluation.

1.6 Project Approach

In order to achieve the project objective, the first task undertaken was a brief review of the relevant regulations and standards, as well as the available research literature on reliability of containment and safety-related structures. Based on this review and C-FERS's previous experience in the area, the models and parameters needed to evaluate the reliability of containment and safety-related structures were identified and assessed. A framework for designing a research program that supports AECB's regulatory activities was then developed on the basis of the information obtained. This framework was discussed in detail with AECB staff to determine AECB's priorities. The research program was then finalized based on all the information collected. The resulting program is described in Sections 2.0 and 3.0 of this report.

2.0 RESEARCH PROGRAM OVERVIEW

The research program is outlined in Figure 1. It is organized in four consecutive major steps dealing with development of the reliability approach, preparation of the required analysis tools, development of specific applications of the methodology, and finally verification. The figure also indicates the report section that deals with each topic. The following comments should be kept in mind in interpreting the proposed program structure:

1. Although Figure 1 shows a logical progression of the main steps, it is not intended as a schedule chart for the program. Initiation of a given step in not dependent on completion of all previous steps, since some overlap between the different steps is possible. A specific schedule would be governed by the degree of dependency between different projects as well as the time and budget constraints of the program.

2. The research areas specified in Figure 1 do not have equal weighting with respect to the level of effort required. Some of them are quire brief, whereas others may need to be divided into several projects.

3. The steps specified at this point are generic and some of the information required under each topic is already available. The specific issues that need to be addressed in further research under each topic are outlined in Section 3.0.

The four main program steps are discussed briefly in this section as follows:

1. *Approach*. This step involves developing a methodology for estimating and evaluating the reliability of containment and safety-related structures with respect to different loading conditions and failure modes.

2. *Analysis tools*. The models and data needed to implement the approach for a given situation will be developed. These include probability models of the applied loads, structural analysis models to estimate the load effects and structural resistance models to determine member response. These components can be used in a reliability analysis methodology to estimate the reliability of any given structural component with respect to a given failure mode.

3. *Applications*. Specific models must be developed to apply the reliability analysis tools in decision making for specific applications. The potential applications are classified into three categories. In Figure 1 the term "design and assessment" is used to describe design-like checks that can be used to verify new designs or assess existing structures. The term "inspection and maintenance" refers to the interpretation of inspection results on prestressing losses for example. Proof and pressure testing involve making inferences regarding structural reliability from test results.

4. *Verification*. It is envisaged that validation and testing of the approaches developed will be necessary to ensure that they can be used with confidence.

In addition to the above, Figure 1 indicates that a process of consultation and communication of results between AECB and the industry would be valuable. This would ensure that the opinions of experts are taken into account in develoing the reliabiity approach and the results are accepted and effectively used by all parties involved.

The specific issues recommended for further research under each of the four steps are discussed in Section 3.0. For each step, an overview of the work proposed is given, followed by a project rationale and objective. A preliminary outline of the tasks that may be required to achieve the objective are also given.

3.0 RESEARCH PROGRAM DESCRIPTION

3.1 Methodology and Framework

Title: Development of a Framework and Methodology for Evaluating the Reliability of Containment and Safety-Related Structures

Rationale:

Design methodologies for containment and safety-related structures have been based on working stress concepts for many years. In order to assess the reliability of these structures, specific performance criteria, expressed in terms of target reliability levels associated with different failure modes, must be clearly defined. Presently these criteria are not well defined, and this has resulted in some difficulties in interpreting and applying the CSA design standards which have been converted to a limit states format.

Objective:

To develop a framework that can be used in evaluating the reliability of containment and safety-related structures with respect to appropriate performance criteria. In addition to the design of new structures, the framework will be applicable to the assessment of existing structures under severe accident scenarios that may result in exceeding the design basis.

Scope:

- Definition of a design philosophy as reflected by a comprehensive set of significant failure modes (*e.g.*, yielding of steel, section collapse, exceeding a specified leakage rate, liner damage).

- Definition of appropriate criteria to evaluate the performance of the structure with respect to each limit state (*e.g.*, should leakage control be based on a no tension condition in the concrete or on a maximum allowable crack width that is related to the allowable leak rate?).

- Assessment of the role of proof testing to 1.15 times the positive design pressure (as specified in Regulatory Document R-7) in relation to the pressure load factor used in the test load combination (CSA-N287.3).

- Definition of acceptable reliability levels for each limit state.

The project will not deal with reliability estimation methods, which have been developed in previous work sponsored by the AECB (Project 2.247.1). The methodology developed can be used in all subsequent reliability estimation related to design of new structures and assessment of existing structures. It will also serve as a basis for revising the format of the relevant CSA standards.

3.2 Development of Reliability Analysis Tools

3.2.1 Loading Processes

Title: Load Models for Containment and Safety-related Structures

Rationale:

Some of the key loading processes acting on containment and safety-related structures, such as earthquake loads, accident pressures and airplane collisions, involve large uncertainties that have not been characterized in the past. Previous work on reliability of CANDU structures, based on approximate load models, shows that these uncertainties have a very significant impact on the estimated reliability (AECB Projects 2.247.1 and 2.247.2). Accurate characterization of these loads would result in a more realistic basis for assessing the safety of containment and safety-related structures.

Objective:

To develop accurate probabilistic models for loads that could affect the performance of containment and safety-related structures.

Scope:

- Evaluation of existing load models to identify those requiring improved models. An initial list includes earthquake loads, accident pressure, hydrogen detonation, airplane collision, and dead load.

- Collection of the necessary information and development of an appropriate probabilistic model for each selected load. For example, to characterize the probability distribution of accident pressure:

  - Characterize model uncertainty associated with accident pressure calculation from model validation data.

  - Review safety studies to determine the probability of occurrence of an accident and the associated pressure level.

  - Include the effect of uncertainties regarding the time to shut down and cooling system operation on the probability distribution of peak pressure.

  - Combine the above into a random process that models the accident pressure.

  For other loads, such as dead load, load survey data may be required. Some work is already in progress to characterize response spectra for earthquakes (AECB Project 2.311.1).

- Based on the load model characteristics, define a method to select the design load in each case (*e.g.*, what return period should be used in defining the accident pressure?).

3.2.2 Structural Analysis

Title: Validation of Simplified Structural Models for Reliability Analysis of Containment Structures

Rationale:

In reliability analysis of containment structures, simplifying assumptions regarding the structural behaviour are usually made in order to keep the computational effort to a manageable level. For example, a cylindrical wall of a containment structure may be modelled as a linear element subject to flexure and axial load, whereas in reality, it is subject to a multi-dimensional state of stress. An analysis of the effect of these simplifying assumptions on reliability estimates is required.

Objective:

To verify the validity of the simplified structural models used in reliability estimation of containment and safety-related structures.

Scope:

- Selection of a test structure for the verification.
- Definition of the load combinations to be used and the corresponding load probability distributions.
- Execution of a finite element analysis of the structure to determine the state of stress under selected load combinations.
- Estimation of reliability based on the finite element model and comparison of the results with those obtained from simplified beam/column models.
- Assessment of the accuracy of the simplified models.

3.2.3 Structural Resistance

Title: Models for Estimating the Capacity of Shear Walls for Reactor Vaults

Rationale:

The estimation of the shear capacity of laterally loaded concrete members is a complex problem with a number of competing solution approaches. Due to this, reliability with respect to shear

capacity has been the weakest aspect in the process of structural reliability evaluation. Since shear walls are used extensively in some types of containment structures, a good model for estimating the probability distribution of shear capacity is required.

Objective:

To select an accurate model for shear capacity of concrete walls (out of the models that already exist in the literature) and characterize the uncertainty associated with its application.

Scope:

- Review existing models for shear capacity.
- Review the literature to find experimental data that can be used to test these models.
- Apply these models to structural members typical of those used for containment and safety-related structures.
- Compare model results to test results and find a practical model that has a small error.
- Develop a probability distribution of the model error for the selected model for use in subsequent reliability analyses.

3.3 Applications

3.3.1 Design and Assessment

Title: Development of a Reliability-based Design and Assessment Approach for Containment and Safety-Related Structures

Rationale:

As an alternative to estimating structural reliability on the basis of detailed probabilistic calculations, it has been shown for many types of structures that deterministic design checks can be calibrated to achieve a specific reliability level. If such reliability-based checks are available (as is the case for man structural codes), demonstration of reliability becomes a simple matter of satisfying the deterministic criteria. The CSA standards for the design of containment and safety-related structures include such checks. These, however, have not been calibrated for specific reliability levels, and are therefore not suitable as a basis for demonstrating reliability. Calibrating these criteria using the framework mentioned in Section 3.2, would result in a set of simplified safety checks that can be used for design evaluations of new structures and assessment of existing structures. The results can also be use as a basis for revising the design standards.

Objective:

To calibrate a generic set of reliability-based design and assessment checks that can be used in safety evaluation of containment and safety-related structures.

Scope:

Some of the work required for this project has already been carried out under previous projects for the AECB (*e.g.*, for load factor verification in AECB Project 2.247.1, and seismic assessment in AECB Project 2.247.2). The aim of the project is to generalize the methodology and produce more definitive and comprehensive results. It is also noted that this project should focus on aspects that are unique to containment and safety-related structures (*e.g.*, leak rate requirements), since many of the provisions of existing building design standards are directly applicable.

- Define the scope of the required checks based on design philosophy for typical design and assessment situations. Focus on aspects that are unique to containment and safety-related structures.

- Using the information gained from previous work (see Sections 3.1 and 3.2), calibrate the load and resistance selection criteria, and the load and resistance factors to ensure that the target reliability levels are met for the limit states considered.

- For the assessment of existing structures develop a generalized approach for the definition of material properties based on structure-specific data if such data exist (addressed for reinforced concrete containment structures in AECB Project 2.247.2).

- Develop guidelines for reliability-based design and assessment of containment and safety related structures.

- Demonstrate application of the guidelines for appropriate test cases.

3.3.2 Inspection and Maintenance

3.3.2.1 Prestressing Losses

There is an on-going project sponsored by AECB (Project 2.247.3) that aims at developing reliability-based guidelines for the assessment of prestressing in bonded and unbonded systems. The need for further work in this area will be determined after completion of this project.

3.3.2.2 Material Deterioration

Title: Inspection of Containment and Safety-related Structures for Material Deterioration

Rationale:

Depending on environmental conditions, concrete structures may be subjected to different deterioration mechanisms such as leaching, sulfate attack and corrosion of reinforcing steel. This subject has received considerable attention in the U.S. and Europe, where research is on-going to characterize deterioration with specific parameters and develop relevant data bases. In Canada, visual inspections are carried out according to a plan developed subjectively by the operator. There is a need to develop a rational approach to assess the impact of material degradation on structural reliability. The resulting approach can be used as a basis for planning inspection programs that ensure adequate structural safety. The scope of the project should include both visual inspection and non destructive testing.

Objective:

To develop guidelines for visual and non destructive inspection of concrete and reinforcing steel in containment and safety-related structures.

Scope:

The first step in this research should be a qualitative assessment by a qualified expert of the problem of concrete deterioration and steel corrosion for CANDU structures. The scope of this includes:

- Assessment of the magnitude of the problem of deterioration in CANDU structures.
- Definition of the conditions that lead to deterioration.
- Investigation of the potential for quantifying the effect of deterioration on concrete strength and section behaviour and identification of possible methods to model it.

The purpose of the following step is to develop an approach for planning and evaluating inspection programs. The approach adopted will depend on the results of the initial phase. Two approaches are possible:

- A qualitative approach based on a subjective safety scoring system. In this approach, the factors affecting deterioration are identified and each structure or element is assigned subjective scores with respect to these parameters. The scores are then combined using a simple reliability-consistent formulation to determine high risk areas that require inspection.
- A quantitative approach based on relating concrete deterioration to environmental parameters. This approach requires the definition of concrete properties and steel area as a function of time depending on environmental conditions or previous observations. Its feasibility can be determined based on the results of the preliminary investigation. If it is deemed feasible, the resulting deterioration model can be used in the overall

reliability estimation methodology to determine the effect of deterioration on reliability and make decisions accordingly.

3.3.3 Proof and Pressure Testing

Title: Utilization of the Results of Pressure Tests to Update the Reliability of Containment Structures

Rationale:

Survival of a pressure test gives a direct indication of the ability of containment to control leakage for pressures less than or equal to the test pressure. It also gives an indirect indication of the leak integrity under higher pressures and the structural resistance to other loads. For example, knowledge that the structure has maintained a low leakage rate under the test pressure indicates that the prestressing forces are high and therefore the probability of yielding of the non-prestressed steel in tension during an earthquake is low. The significance of the information obtained from the test depends on the test pressure; more significant information is obtained from higher test pressures. Presently, models to calculate the structural reliability of containment structures based on the results of a pressure test are not available. Such models can be useful in planning pressure test requirements with respect to pressure level and testing interval.

Objective:

To develop a model for estimating the structural reliability of a containment structure with respect to different limit states based on the results of a pressure test.

Scope:

- Analyze present practices in the use of pressure tests.
- Develop a model to calculate the probability of failure for different limit states based on the test results.
- Test the model for representative structures.
- Develop guidelines for the use and interpretation of pressure tests.

3.4 Testing and Validation

Title: Validation of the Reliability Approach as a Basis for Design and Assessment of Containment and Safety-Related Structures

Rationale:

To make practical use of the results produced by the research projects described in Section 3.1

to 3.3, the applicability of these results should be demonstrated for some typical structures. This would validate the conclusions made and provide the opportunity to revise and adjust conclusions where necessary. Some verification activities were built into the projects discussed in the previous sections. However, a separate verification project is necessary to ensure consistency of the overall methodology.

Objective:

To ensure practicality of the procedures and recommendations resulting from different projects in the reliability-based program, by testing their performance for realistic cases corresponding to typical containment and safety-related structures.

Scope:

- Define a set of test structures that represent a sufficiently broad range of containment and safety-related structures.

- Collect all the necessary information for the test structures including design loads, material properties, section dimensions, pressure test reports, and in-service inspection data.

- Apply the research results to the different test structures as appropriate.

- Assess the results with respect to availability of the required data, ease of application by structural engineers, usefulness of the outputs, and relevance to decision making.

- Identify the benefits of the reliability-based approach as compared to other approaches currently used by the industry.

As indicated in Figure 1, this project can be carried out concurrently with the projects described in Sections 3.1 to 3.3

4.0 CONCLUDING REMARKS

A research program in the area of structural reliability of containment and safety-related structures has been developed. The goal of the research program is to develop approaches that can be used by AECB staff to evaluate the safety of these structures. The proposed projects have been selected to address deficiencies in the available models and information required to achieve this goal.

The proposed projects focus on the following topics:

- Reliability methodology for assessment of containment and safety-related structures.
- Uncertainties associated with design basis loads such as accident pressures, hydrogen detonation, seismic loads and airplane collisions.
- Validation of simplified structural models as a basis for reliability analysis.
- Shear strength models for reinforced concrete walls for reactor vaults.
- Generic reliability-based design and assessment checks.
- Inspection and maintenance to detect material deterioration.
- Updating reliability based on pressure test results.

These topics have been defined on the basis of need for information and potential success. It is felt that all of these projects address important topics that are required for successful application of reliability techniques to safety evaluation. It is also felt, based on a preliminary assessment, that progress can be made towards advancing the state-of-the-art in each of the proposed subject areas.

It is recognized, however, that other issues must be taken into account in prioritizing these projects, and developing a specific schedule and resource allocation scheme for their execution. These issues include resource availability, preferred size of each project, perceived urgency, and the degree of progress (*i.e.*, value for money) that can be achieved in each case. This report provides a basis for considering these issues in the development of a specific research program on reliability-based assessment of containment and safety-related structures.

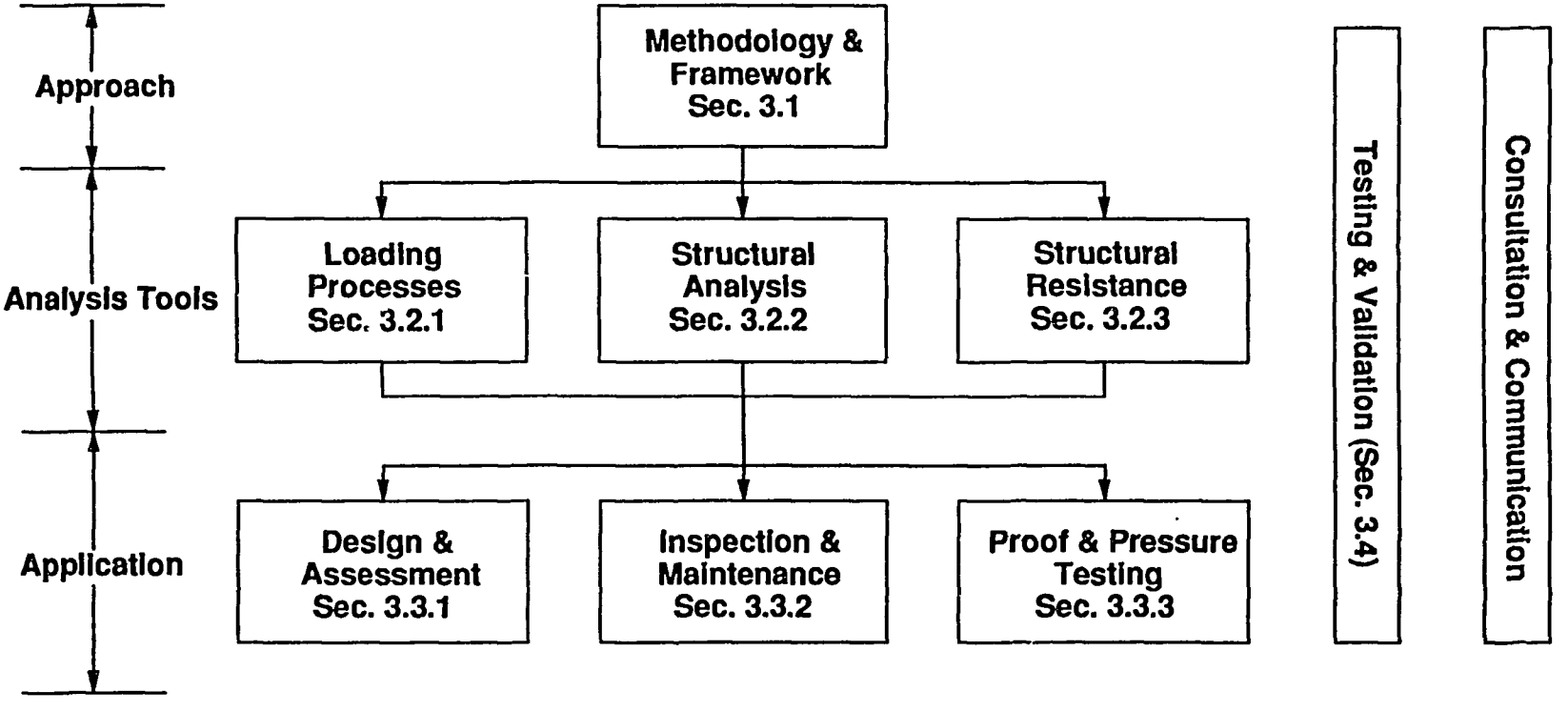

Figure 1 Overview of Research Program