International Technology Scanning Program

Assuring Bridge Safety and Serviceability in Europe



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16. Abstract

U.S. engineers need advanced tools and protocols to better assess and assure safety and serviceability of bridges. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a scanning study of Europe to identify best practices and processes to assure bridge safety and serviceability.

The scan team found that the European highway agencies expect their bridge programs to not only ensure user safety, but also to meet serviceability expectations and enhance capital investment decisions. The team gathered information on safety and serviceability practices and technologies related to design, construction, and operations.

Team recommendations for U.S. implementation include developing a national strategy to increase use of refined analysis for bridge design and evaluation, encouraging States to use refined analysis combined with reliability analysis to avoid unnecessary rehabilitation or replacement of bridges, and encouraging adoption of the concept of annual probability of failure to quantify safety in probability-based design and rating specifications.

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Assuring Bridge Safety and Serviceability in Europe

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International Technology Scanning Program

THE INTERNATIONAL TECHNOLOGY SCANNING Program, sponsored by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP), evaluates innovative foreign technologies and practices that could significantly benefit U.S. highway transportation systems. This approach allows advanced technology to be adapted and put into practice much more efficiently without spending scarce research funds to re-create advances already developed by other countries.

FHWA and AASHTO, with recommendations from NCHRP, jointly determine priority topics for teams of U.S. experts to study. Teams in the specific areas being investigated are formed and sent to countries where significant advances and innovations have been made in technology, management practices, organizational structure, program delivery, and financing. Scan teams usually include representatives from FHWA, State departments of transportation, local governments, transportation trade and research groups, the private sector, and academia.

After a scan is completed, team members evaluate findings and develop comprehensive reports, including recommendations for further research and pilot projects to verify the value of adapting innovations for U.S. use. Scan reports, as well as the results of pilot programs and research, are circulated throughout the country to State and local transportation officials and the private sector. Since 1990, more than 80 international scans have been organized on topics such as pavements, bridge construction and maintenance, contracting, intermodal transport, organizational management, winter road maintenance, safety, intelligent transportation systems, planning, and policy.

The International Technology Scanning Program has resulted in significant improvements and savings in road program technologies and practices throughout the United States. In some cases, scan studies have facilitated joint research and technology-sharing projects with international counterparts, further conserving resources and advancing the state of the art. Scan studies have also exposed transportation professionals to remarkable advancements and inspired implementation of hundreds of innovations. The result: large savings of research dollars and time, as well as significant improvements in the Nation's transportation system.

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Table of Contents

Executive Summary 1
- Background 1
- Summary of Initial Findings 2
- Recommendations 2
- Implementation Activities 2

Chapter One: Introduction 3
- Background 3
- Scan Team 3
- Amplifying Questions 4
- Host Countries 4

Chapter Two: Findings on Assuring Bridge Safety and Serviceability 7
- Eurocodes 7
  - Background 7
  - Vehicular Live Loads and Live Load Factors 9
- Refined Methods of Analyzing, Designing, and Assessing Bridges 10
  - Finite Element Analysis of New Bridges 10
  - Finite Element Analysis of Existing Bridges. 13
  - Weigh-in-Motion Data 14
- Use of Enhanced Reliability Analysis to Assess Safety 14
  - Quantification of Safety 14
  - Bridge Operations 15
- Quality Assurance/Quality Control 15
  - Design Checks 15
  - Inspection 16
  - Laser Scanning 17
  - QA/QC in the United Kingdom 17
- Processes and Practices to Provide Serviceability and Durability. 18

Chapter Three: Recommendations and Implementation Activities 25
- Recommendations. 25
- Implementation Activities. 26

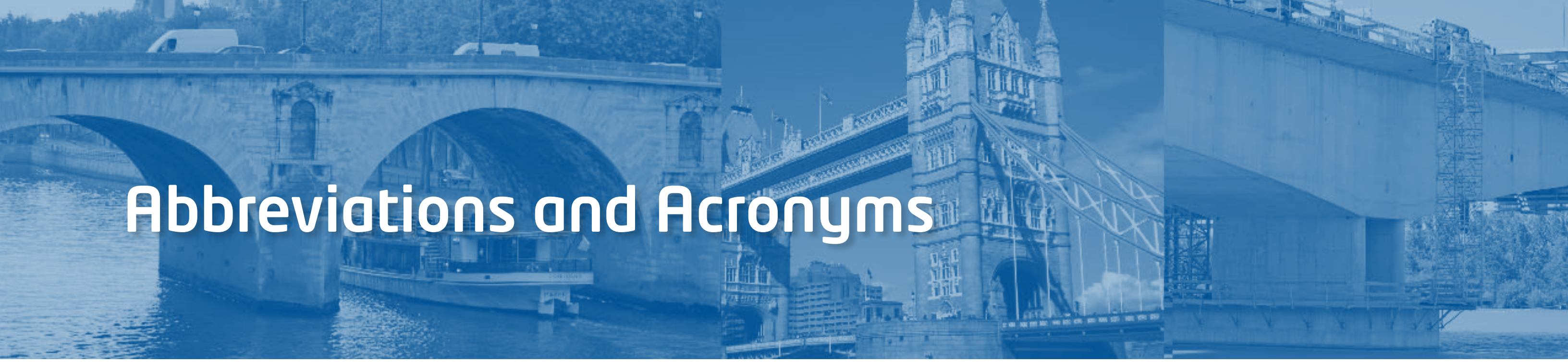
Appendix A: Amplifying Questions. 29
Appendix B: Scan Team Members. 33
Appendix C: Host Country Contacts 37
Appendix D: Finnish Statistical Process Controls in the Bridge Inspection Program 45

Figures

Figure 1. Scan team members. 4
Figure 2. Hierarchy of Eurocodes on concrete bridge design.. 8
Figure 3. German live load. 9
Figure 4. Finnish live load used for rating.. 11
Figure 5. Change management. 12
Figure 6. Weigh-in-motion data. 13
Figure 7. Contractual relationship of the check engineer. 16
Figure 8. Finnish statistical process control.. 17
Figure 9. Laser scanning of structures in Finland. 17
Figure 10. Detail of drag plate used in Austrian integral bridges. 19
Figure 11. Crack width control. 20
Figure 12. External post-tensioning.. 21
Figure 13. Typical two-girder system in Europe. 21
Figure 14. Maximum allowed values for the deviation PL and relative deviations SP and SPkust. 46
Figure 15. Plot of divergence indicator from Finnra quality reports. 46
Figure 16. Example calculation of Finnra quality parameters. 47

Tables

Table 1. Scan itinerary. 5
Table 2. Eurocode consequence classes. 14
Table 3. Inherent probabilities of failure (P_f) and corresponding reliability indices (β). 14
Table 4. Quality control inspections in 2005.. 45



Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASFiNAG	Autobahnen- und Schnellstraßen- Finanzierungs- Aktiengesellschaft
BASt	Bundesanstalt für Straßenwesen (Federal Highway Research Institute)
CTOA	Centre Technique des Ouvrages d'Art
DOT	department of transportation
EU	European Union
FEM	finite element method
FHWA	Federal Highway Administration
Finnra	Finnish Road Administration
GIS	geographic information system
HA	Highways Agency
HGV	heavy goods vehicle
LCPC	Laboratoire Central des Ponts et Chaussées
LRFD	load and resistance factor design
LRFR	load and resistance factor rating
MR&R	maintenance repair and rehabilitation
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NDE	nondestructive evaluation
NDPs	Nationally Determined Parameters
QA/QC	quality assurance/quality control
Sétra	Service d'Etudes Techniques des Routes et Autoroutes
TRB	Transportation Research Board
WIM	weigh-in-motion

Executive Summary

Background

U.S. engineers need new, advanced tools and protocols to better assess and assure safety and serviceability of highway bridges. These tools include an overall, integrated approach to bridge analysis, design, evaluation, and load-carrying capacity (load rating). Present-day design specifications (load and resistance factor design (LRFD)) have assured safety by analyzing the effect of heavy, legal trucks throughout the United States and applying calibration protocol using limited Canadian site statistics. However, the calibration did not include serviceability calibration to assure bridge serviceability and performance. Therefore, it is desirable to identify design practices, design truck assessments, and detailed code calibration procedures used in other countries to assure the safety and serviceability of newly designed bridges.

The new American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Evaluation* was developed to assist bridge owners by establishing inspection, evaluation, load rating, and posting practices and procedures. The load and resistance factor rating (LRFR) section of the manual is based on reliability theories to assure a certain level of safety for members. However, certain serviceability checks were left optional because they are not directly related to bridge safety, but are geared to protecting the long-term serviceability and durability of structures. It is unclear whether making these checks optional has an effect on the service life of aging U.S. bridges. Therefore, it is desirable to identify evaluation (load-carrying assessment) best practices and quantify the required level of safety and performance used in other countries to avoid failures, serviceability concerns, unnecessary expenditures, and traffic restrictions.

Knowledge and software have evolved to enable moving away from line girder approximate procedures to a system approach using advanced finite element analyses. However, current U.S. specifications and practice still, for the most part, rely on simplified, approximate analyses to determine the structural effects of vehicular loading on bridge girders. Situations impeding the use of advanced analysis in design and evaluation include the cost of software, lack of training, lack of guidance materials, modeling complexities, and perceived high cost-to-benefit ratio. A growing number of U.S. bridge owners and engineers seek to expand and mainstream the use of more rigorous design and evaluation approaches in everyday practice to achieve more economical use of materials, a better understanding of the structural system, and a better quantified level of safety and serviceability.

The purpose of the scan was to identify best practices and processes to assure bridge safety and serviceability for implementation in the United States. Specific topics of interest included the following:

- Safety and serviceability—design and construction
- Safety and serviceability—operations
- Refined analysis—design, construction, and operations

The team developed a comprehensive list of technical and operational process questions, including topics on safety and serviceability concerns and the use of refined analysis during the design, construction, and operational phases of a bridge's life (Appendix A).

An 11-member team was formed to conduct the study. This team consisted of three representatives from the Federal Highway Administration (FHWA), four representatives from State departments of transportation, one representative from academia, and three structural engineering design consultants, one who served as the report facilitator.

The team conducted a series of meetings and site visits with representatives of government agencies and private sector organizations abroad from May 29 to June 14, 2009. The team visited Austria, England, Finland, France, and Germany. These five countries were selected through a desk scan that identified their use of advanced activities in assuring bridge safety and serviceability.

Summary of Initial Findings

The scan team found that, as in the United States, the European host agencies put a tremendous value on bridge programs not only to ensure highway user safety, but also to ensure that durability and serviceability expectations are met and to enhance capital investment decisions on the existing bridge inventory. They place major emphasis on ensuring that there is no service interruption because of a bridge failure or major repair, and that appropriate sophisticated methods are used to evaluate structural safety. Most of the agencies visited had major programs aimed at assuring accuracy of design and rating of highway structures on their systems.

The scan team also identified many practices and technologies related to the topics of interest. The order in which they are presented in this report is for clarity of presentation and does not reflect the priority recommended by the team.

Recommendations

Based on the above findings, the recommendations of the team are as follows:

1. Develop a nationally accepted strategy for promoting and increasing the practicing bridge engineer's use of refined analysis for design and evaluation.

2. Encourage States to use refined analysis for evaluation in combination with reliability analysis to avoid unnecessary posting, rehabilitation, or replacement of bridge structures.

3. Encourage the AASHTO Subcommittee on Bridges and Structures to adopt the concept of annual probability of failure (exceedance) as the quantification of safety in its probability-based design and rating specifications rather than the reliability index for a 75-year design life.

4. Conduct research to create the basis to systematically introduce increasing levels of sophistication into analyses and load models with the objective of assessing bridges more accurately.

5. Encourage owners to periodically and routinely reassess traffic highway loading, using recent weigh-in-motion data, to ensure that their live load model adequately provides for bridge safety and serviceability for the desired service life and level of safety.

6. Encourage States to develop an overweight permit design vehicle and design for the associated AASHTO Strength II load combination, the load combination meant to consider special permit truck loads during the design of a bridge, particularly in high-load corridors.

7. Initiate and maintain a database documenting bridge failures around the world, including sufficient information and data to assist in assessing the causes of failure, for the purpose of proactively examining U.S. practices and avoiding similar problems in the United States.

8. Continue efforts to develop guidelines and training for proper use of nondestructive techniques to detect corrosion and breakage of cables of cable-supported bridges and internal and external tendons of post-tensioned bridges.

9. Explore independent check engineering and check engineer certification to augment quality assurance and quality control of bridge designs.

10. Initiate an investigation and technology transfer of selected best practices and emerging technologies identified during the scan. Potential candidates are outlined in this report.

Implementation Activities

The scan team developed a detailed implementation plan for the recommended initiatives and practices. Included in the plan are technical presentations and written papers at national meetings and conferences sponsored by FHWA, AASHTO, the Transportation Research Board, and other organizations to disseminate information from the scan. Also included in the plan is coordination with AASHTO and FHWA to advance these initiatives and practices and to assist with the development of new FHWA and AASHTO standards and guidelines governing bridge design and analysis. These and other planned activities are discussed in Chapter 3.

CHAPTER 1

Introduction

Background

New, advanced tools and protocols are available to help bridge engineers better assess and assure safety and serviceability of highway bridges. These tools include an overall, integrated approach to bridge analysis, design, evaluation, and determination of load-carrying capacity (load rating). Present-day design specifications (load and resistance factor design (LRFD)) assure safety by analyzing the effect of heavy, legal trucks throughout the United States and comparing that effect to a protocol calibrated using limited but very reliable Canadian site statistics. However, the calibration did not include serviceability calibration to assure bridge serviceability and performance, and it did not use comprehensive statistics available in the United States because the available weigh-in-motion (WIM) data was deemed unreliable. Therefore, it is desirable to identify design practices, design truck assessments, and detailed code calibration procedures used in other countries to assure the safety and serviceability of newly designed bridges.

The American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Evaluation* was developed to assist bridge owners by establishing inspection, evaluation, load rating, and posting practices and procedures. The load and resistance factor rating (LRFR) section of the manual is based on reliability theory to assure a certain level of safety for members. However, certain serviceability checks were left optional because they are not directly related to bridge safety, but are geared to protecting the long-term serviceability and durability of structures. It is unclear whether making these checks improves the service life of aging U.S. bridges. Therefore, it is desirable to identify good evaluation (load-carrying assessment) practices, including a quantification of the corresponding level of safety and performance, used in other countries to avoid failures, serviceability concerns, unnecessary expenditures, and traffic restrictions.

In addition, knowledge and software have evolved to enable moving away from line girder, one-dimensional approximate analytical models to a system analysis using refined two-dimensional (2-D) or three-dimensional (3-D) analytical models. However, current U.S. specifications and practice still rely heavily on simplified, approximate analyses to determine the structural effects of vehicular loading on bridge girders. Situations impeding the use of advanced analyses in design and evaluation include lack of adequate software training, lack of guidance material, specifications, complexity, and perceived high cost-to-benefit ratio. A migration to the use of more rigorous design and evaluation approaches in everyday practice for both simple and complex bridges may result in a more economical use of materials, a better understanding of structural reliability, and a better quantification of safety and serviceability.

Scan Team

An 11-member team was formed to study European practices (figure 1). This team consisted of three representatives from the Federal Highway Administration (FHWA), four representatives from State departments of transportation (DOTs), one representative from academia, and three structural engineering design consultants, one who served as the report facilitator (see Appendix B).

The purpose of the team's study was to identify best practices and processes to assure bridge safety and serviceability for consideration by U.S. engineers. The team generated a comprehensive list of technical and operational process questions, including safety and serviceability concerns and the use of refined analysis during the design, construction, and operational phases of a bridge's life. (Refined analysis is defined as analysis beyond one-dimensional structural analysis using lateral live-load distribution factors.) These questions were forwarded to the hosts for their use in preparing for the team's visit.

Specific topics of interest to the team included the following:

- Use of advanced refined methods of analyzing, designing, and assessing highway structures for safety and serviceability during design and construction

- Use of enhanced reliability analysis to assess safety and serviceability during operations
- Quality assurance and quality control (QA/QC)
- Use of performance-based approaches for durable structures
- Use of refined analysis during design, construction, and operations

Figure 1. *Scan team members.*

Amplifying Questions

Amplifying questions were developed to help the foreign experts more fully understand the topics of interest to the scan team members. These questions, in Appendix A, were provided to the host countries before the scan. The contacts in each country are in Appendix C, and the scan itinerary is in table 1.

Host Countries

The team conducted a series of meetings and site visits with representatives of government agencies and private sector organizations abroad from May 29 to June 14, 2009. The panel visited Austria, England, Finland, France, and Germany. These five countries were selected through a desk scan of their advanced activities in assuring bridge safety and serviceability. Details of the team's meetings are shown in table 1.

Table 1. *Scan itinerary.*

Date	Location	Activities
Monday, June 1, 2009	**Helsinki, Finland**	Meeting at the Finnish Road Administration (Finnra). Heard presentations on Finnra bridge management system, bridge inspections, bridge design and building processes and methods, implementation of Eurocodes, bridge loading tests, bridge monitoring, and bridge bearing capacity calculations.
Tuesday, June 2, 2009	**Vienna, Austria**	Meeting at the Federal Ministry for Transport, Innovation, and Technology. Heard presentations on safety inspection and investigation of bridges, training and certification of bridge inspectors, asset management of bridges, bridge WIM and reliability assessment of existing bridge structures, research on load-carrying capacity of existing bridges, and experiences and research on bridge monitoring.
Wednesday, June 3, 2009	**Vienna, Austria**	Meeting at the Federal Ministry for Transport, Innovation, and Technology. Heard presentations on integrated approach to the evaluation of the capacity of existing bridges, bridge life-cycle costing, new requirements for strengthening bridges with top concrete, state-of-the art design and maintenance of bridges without joints and bearings, and monitoring and numerical simulation of bridges without joints and bearings.
Thursday, June 4, 2009	**Graz, Austria**	Meeting at Graz University of Technology. Heard presentations on an approach for improving safety and serviceability from the design phase through the life cycle using bridge information modeling, investigation of high-speed suitability of existing and new railway bridges, lessons learned on highway bridges in Slovenia, and bridge design using ultra high-performance concrete. Visited the Laboratory for Structural Concrete and the construction site of the Traismauer Bridge across the Danube River.
Friday, June 5, 2009	**Cologne, Germany**	Meeting at the Federal Highway Research Institute (BASt). Heard presentations on bridge inventory and condition, traffic on German highways, heavy goods vehicle (HGV) weights and dimensions, HGV traffic with special permission, traffic load models, calibration, use of WIM data, future developments, Eurocodes for bridges, QA/QC procedures for bridge analysis and design, assessment of bridges, and refined analysis.
Monday, June 8, 2009	**Paris, France**	Meeting at the Center for Technical Studies of Highways and Motorways (Sétra). Heard presentations at the Central Laboratory for Bridges and Highways (LCPC) on Sétra and the Technical Center for Bridges (CTOA), Eurocode principles of safety verification, concrete durability, fatigue assessment of steel bridges, existing methodologies of assessment, and a case study on assessment of the loading resistance of the Pont d'Aquitaine.
Tuesday, June 9, 2009	**Paris, France**	Meeting at LCPC. Received an overview of LCPC research units, including highlights of research activity on bridges. Heard presentations on bridge WIM for load assessment and load effect calculations, CESAR-LCPC finite element code, and reassessment of bridges affected by alkali-aggregate reaction and delayed ettringite reaction. Visited the Large-Scale Structural Testing Laboratory and learned about structural investigation methods and specific techniques for portland cement bridges, dynamic investigation, structure durability and reliability, and risk analysis on multispan post-tensioned girder bridges.
Wednesday, June 10, 2009	**London, United Kingdom**	Meeting at the Institute for Civil Engineers (ICE). Heard presentations by the U.K. Highways Agency (HA) on structure assets, key processes, standards, design and operational framework, inspection and technical approval, design (including innovative structures), loading, operations (including assessment), inspection, information systems, integrated asset management, and maintaining agents. A case study focused on the Midland Links motorway elevated structures.
Thursday, June 11, 2009	**Cambridge, United Kingdom**	Meeting at King's College at Cambridge University. Heard presentations on U.K. bridge management, findings of an audit of the assessment program and management of substandard structures, probabilistic approaches, advanced assessment and analysis techniques, monitoring and sensor technologies, procurement strategies, and an overview of Eurocodes and new materials for bridges.
Friday, June 12, 2009	**London, United Kingdom**	Meeting at ICE. Heard presentations by software providers on developments and trends in software use for U.K. bridges, HA input on the analysis of bridges through the technical approval process, role of design and analysis software in assuring bridge safety, testing and validation of bridge design and analysis software, and Eurocodes and software applications.

CHAPTER 2

Findings on Assuring Bridge Safety and Serviceability

THE SCAN TEAM FOUND THAT THE EUROPEAN host agencies place tremendous value on their bridge programs not only to ensure highway user safety, but also to ensure that durability and serviceability expectations are met and to enhance capital investment decisions on the existing bridge inventory. They place major emphasis on ensuring that there is no service interruption because of a bridge failure and that appropriate methods are used to evaluate structures to ensure structural safety. Virtually all of the agencies visited had major programs aimed at assuring accuracy of design and rating of highway structures on their systems.

Specifically, the team noted the following:

- The Finnish Ministry of Transport and Finnra set condition targets each year, based on a weighted sum of damage points.
- Austria has a goal of no more than 5 percent of its bridge inventory with a rating of 4 or 5 (on a scale of 1 to 5) by 2012.
- France sets its maintenance budget to assure that less than 2 percent of its bridges are in the worst category.

Bridge Serviceability and Durability

Bridge serviceability and durability are defined in Eurocode 2 on concrete structures as follows:

> *"A durable structure shall meet the requirements of serviceability, strength and stability throughout its intended working life, without significant loss of utility or excessive unforeseen maintenance.*
>
> *"The required protection of the structure is established by considering its intended use, service life, maintenance programme and actions. The possible significance of direct and indirect actions, environmental conditions and consequential effects are also considered."*

SOURCE: PASCAL CHARLES, CENTRE TECHNIQUE DES OUVRAGES D'ART

The scan team identified many practices and technologies related to its topics of interest. These topic areas are discussed in this chapter. The order in which they are presented is for clarity of presentation and does not reflect the team's recommendation for priority.

Eurocodes

The European Union (EU) is in the process of making major revisions to its codes to provide more uniform bridge standards across member countries. This event has provided an opportunity for EU member states to take a critical look at past practices and perform various studies to improve the overall performance of bridges on their roadways. Two of the countries visited had help desks to assist users during this transition time.

Background

In 1975 the Commission of the European Communities began actions to develop a new building code for use by EU nations based on Article 95 of the Treaty of Rome. The objective, established by Article 95, was to eliminate technical obstacles to trade and harmonize technical specifications across its member states. As they pertain to structural design, these harmonizing technical rules establish a set of common codes for the design of buildings and civil engineering works that replace a variety of differing rules being followed across the continent (figure 2, see next page). The intention is for the structural Eurocodes to be implemented by the various member states by the end of 2010.

The Structural Eurocodes consist of several parts:

EN 1990—Eurocode: Basis of Structural Design
EN 1991—Eurocode 1: Actions on Structures
EN 1992—Eurocode 2: Design of Concrete Structures
EN 1993—Eurocode 3: Design of Steel Structures
EN 1994—Eurocode 4: Design of Composite Steel and Concrete Structures
EN 1995—Eurocode 5: Design of Timber Structures

EN 1996—Eurocode 6: Design of Masonry Structures
EN 1997—Eurocode 7: Geotechnical Design
EN 1998—Eurocode 8: Design of Structures for Earthquake Resistance
EN 1999—Eurocode 9: Design of Aluminium Structures

For bridges, the service life is set at 100 years. The Eurocodes allow national choices in design, mainly through the selection of the numerical values for partial safety factors and other allowables, referred to as Nationally Determined Parameters (NDPs). These national choices are published in a National Annex for each nation. In this way, the nations are allowed, within limits, to choose the level of safety, considering local conditions, applicable to bridges in their countries. Justifications for these national choices include the following:

- Differences in geographical or climatic conditions
- Differences in traffic loads
- Different levels of safety provided or desired in the jurisdiction

The determination of safety levels, including aspects of durability and economy, has always been considered to be

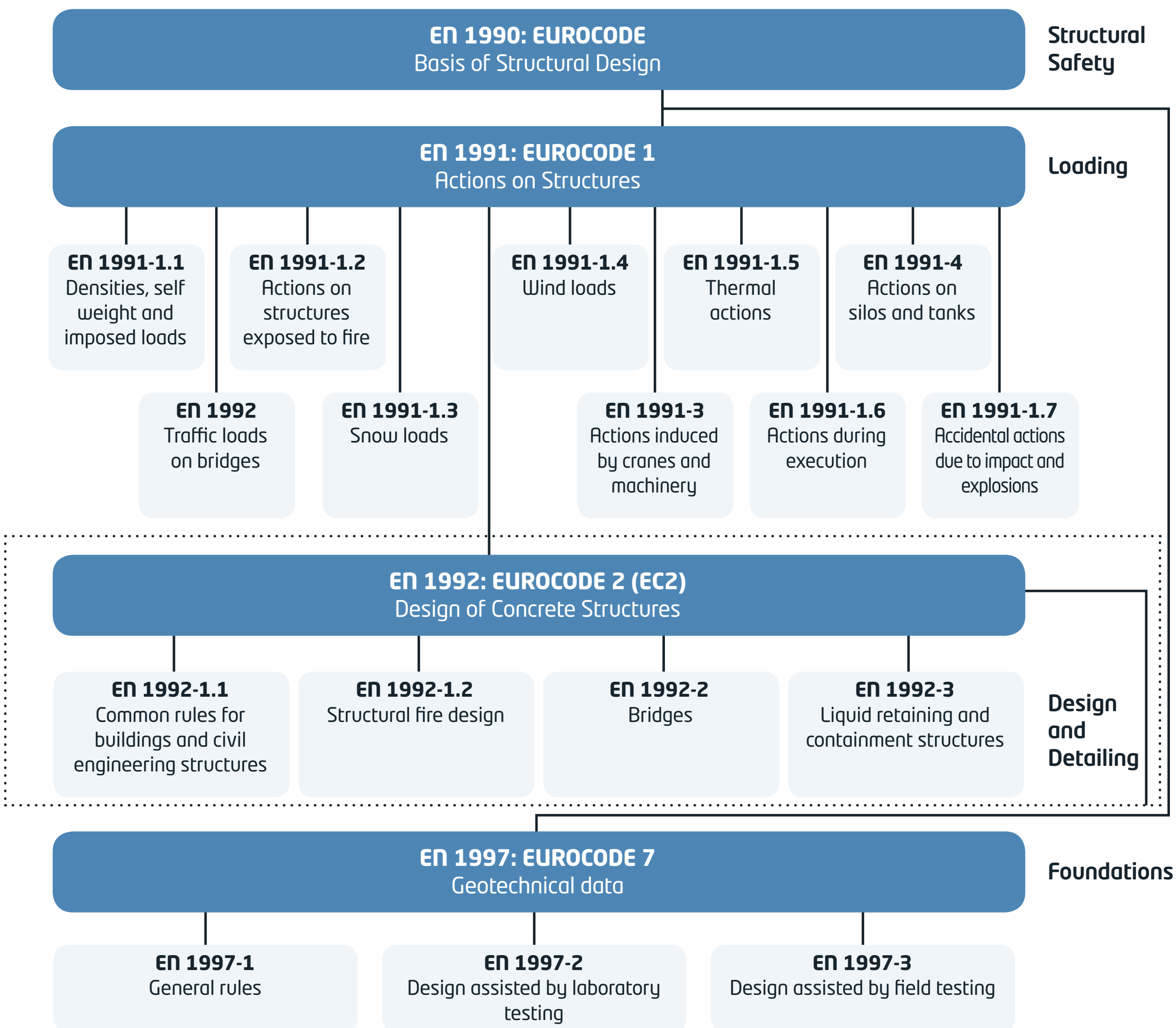
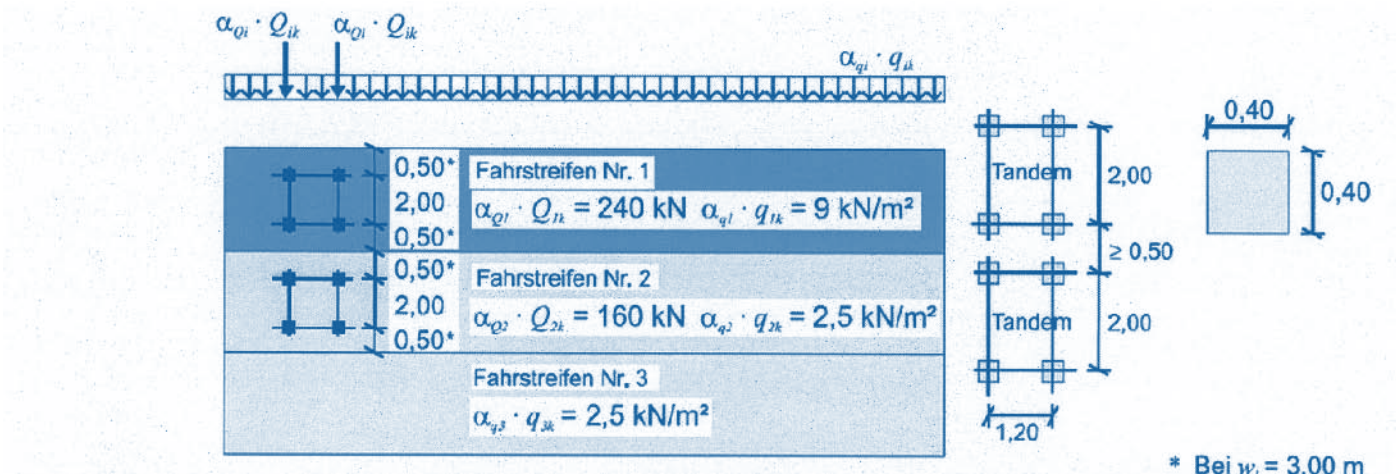


Figure 2. *Hierarchy of Eurocodes on concrete bridge design.*

within the competence and authority of individual member nations. Possible differences in geographical or climatic conditions, as well as different levels of protection that may exist at national, regional, and local levels, can be taken into consideration at the national level through specific design parameters, which are identified in each Eurocode part as NDPs. Therefore, member nations have choices in the codes on safety levels, including aspects of durability and economy that may pertain in their territory. Reliability levels for a member nation may be based on past successful design practice. Member nations are encouraged to use the recommended values for the design parameters in the Eurocodes unless divergence is essential. Malaysia and Viet Nam are expected to adopt the Eurocode; China, Russia, South Africa, and Thailand have held Eurocode seminars.

Vehicular Live Loads and Live Load Factors

Of particular interest to the scan team were vehicular live loads and NDPs for the vehicular live load factor. Figure 3 is an example of live loads used in Germany. The National Annex allows individual nations to adjust the design live load for local legal and permit load levels, as well as for desired levels of operation, maintenance, and enforcement practices.



Stellung	Doppelachse Grundwert	α_{Qi}	angepasster Grundwert	gleichmäßig verteilte Last
	Achslast Q_{ik} in KN		Achslast α_{Qi} * Q_{ik} in KN	q_{ik} (oder q_{rk}) in KN/m²
Fahrstreifen 1	300	0,8	240	9,0
Fahrstreifen 2	200	0,8	160	2,5
Fahrstreifen 3	0	-	0	2,5
andere Fahrstreifen	0	-	0	2,5
Restfläche (q_{rk})	0	-	0	2,5

Road traffic approval regulations	
Gross vehicle weight	
vehicle or trailer with 2 axles	18,0 t
vehicle or trailer with 3 axles	24,0 t – 28,0 t
vehicle with more than 3 axles	32,0 t
vehicle combinations with less than 4 axles	28,0 t
vehicle combinations with 4 axles	35,0 t – 38,0 t
vehicle combinations with more than 4 axles	40,0 t (44,0 t)

Figure 3. *German live load.*

Austria and the United Kingdom use an NDP of 1.0 factor on the 44-ton truck, and France is considering a smaller five-axle 40-ton truck (44-ton if a double-hauler is used). The 44-ton truck in Eurocode 1-2 (EN 1001-2) can be adjusted as it is in Finland, where a 60-ton truck with seven or eight axles is used in the logging industry (figure 4). This load model is used in the evaluation of load-carrying capacity for existing bridges. In Finland the local legal and permit load level is not given in the National Annex, but in the special statute for motor vehicles.

Refined Methods of Analyzing, Designing, and Assessing Bridges

Finite Element Analysis of New Bridges

The AASHTO *LRFD Bridge Design Specifications* categorize analysis methods as approximate or refined. The approximate methods of analysis, specified in LRFD Article 4.6.2.2, are those for which a live-load distribution factor is quantified through tabularized equations and used in the analysis of single beams (sometimes termed one-dimensional analysis). These lateral live-load distribution factors and the tributary dead-load areas are applied to a one-dimensional model. Refined methods of analysis, discussed in LRFD Article 4.6.3.3, are all other methods in which distribution factors are not used and the bridge is represented as a 2-D or 3-D model. In the United States, their application is limited to unique or complex bridges, bridges deemed substandard using approximate analysis, analysis of nonstandard permit loads, and other special cases. While developing the lateral live-load distribution factors of the *LRFD Specifications,* Zokaie et a1[1] found little benefit in the application of 3-D models beyond simpler 2-D models.

Bridges in Austria, Finland, France, Germany, and the United Kingdom are typically analyzed using refined methods of analysis, defined as analysis using 2-D or 3-D models. Approximate methods of analysis such as load distribution factors are not covered in the Eurocodes and are used only occasionally to check calculations in the countries the scan team visited. The U.K. BD 79, in fact, prohibits the use of line-girder analysis. Austria, Finland, and Germany typically use 2-D models and reserve 3-D models for special cases. Modeling using beam, plate, and shell elements is most common; volume (brick) elements are not commonly used except in research.

Grillage or beam-shell analysis appeared to be routine in the countries visited because of the following:

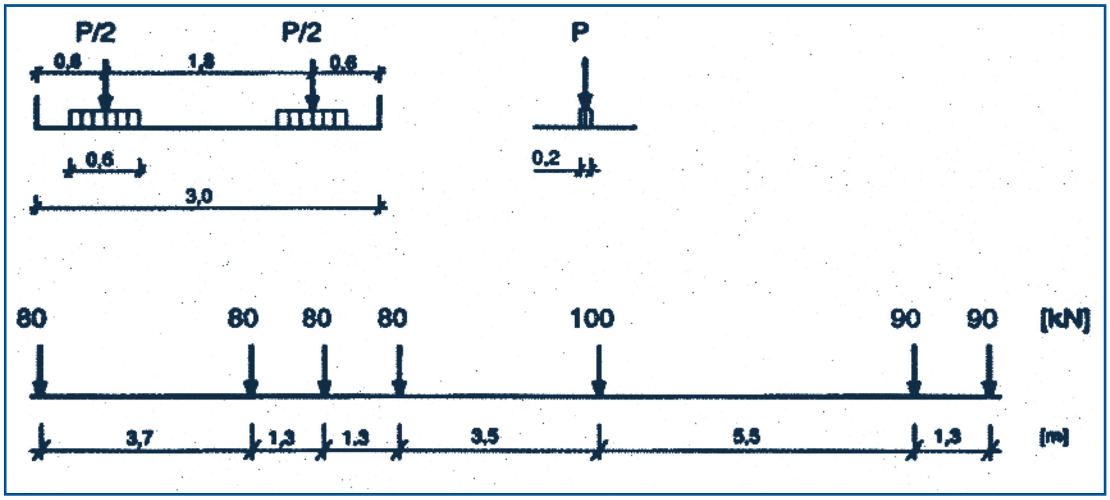
- Decades of acceptance in the European bridge design community
- Cultural emphasis on understanding the structural behavior and graphics capabilities with refined analysis to provide visual confirmation of model correctness
- Software availability specifically for bridge analysis
- Training by software vendors
- Perception by designers of not being a monumental task
- On-the-job-oversight, especially of young engineers' models (A European engineer who had spent time at a U.S. university, as well as a scan team member who had studied a year in Europe, noted that the expertise level of young engineers was more homogeneous in the European Union than in the United States, which could play a role in the widespread feasibility of refined analysis.)
- No overly prescriptive guidelines or restrictions in the Eurocode

The *LRFD Specifications* do not differentiate between force effects determined through approximate or refined analysis. The *LRFD Specifications* inherently assume that the results of analysis, whether approximate or refined, are correct. Thus, if force effects determined through refined analysis are more accurate, the use of refined analysis in applying the *LRFD Specifications* yields reliability indices, ß's, closer in agreement to the target reliability index, $ß_T$, of 3.5. While this is a satisfying result from an academic point of view, it is not a compelling reason for owners to mandate refined analysis if additional analysis effort is required.

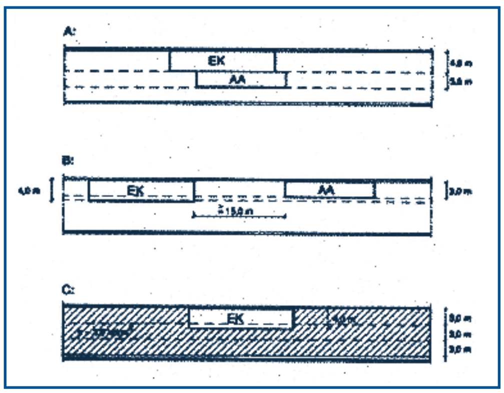
During the development of the first edition of the *LRFD Specifications,* the concept of an analysis factor was considered. Such an analysis factor could differentiate between force effects from approximate or refined analysis by considering the uncertainty of the various methods. Theoretically, more effort in analysis could be rewarded through an analysis factor. These analysis factors would be analogous to the load modifier of Article 1.3.2.1 of the *LRFD Specifications*. Ultimately, the concept of an analysis factor for the *LRFD Specifications* was dismissed because of a lack of data on the uncertainties of the various analysis methods.

[1] Zokaie, T., T. A. Osterkamp, and R. A. Imbsen. 1991. *Distribution of Wheel Loads on Highway Bridges,* NCHRP Report 12-2611. Transportation Research Board, National Research Council, Washington, DC.

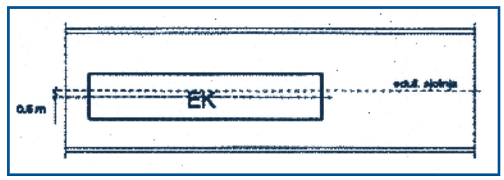
Normal heavy vehicle, truck with trailer, 60 t



Placing of vehicles (special heavy + normal)



Placing of controlled transportation



Load safety factors		**y (normal)**	**y (lowered safety)**
Permanent loads		**1,20 or 0,90**	**1,10**
Traffic loads, weight limit assessment			
• 1 AA-vehicle		1,45	1,30
• 2 AA-vehicles		1,30	1,10
• 1 AA vehicle + UDL kN/m²		1,30	1,10
Traffic loads, capacity for special heavy transportations			
a) Controlled transportation	EK	1,20	1,10
b) General transportation			
• 1 EK-vehicle	EK	1,30	1,15
• AA + EK -vehicles	EK	1,20	1,00
	AA	1,30	1,15
• EK + UDL 3 kN/m²	EK	1,20	1,00
	UDL	1,30	1,15

Figure 4. *Finnish live load used for rating.*

In the countries visited, design was not always integrated with analysis and code checks. The following are additional scan team observations:

- The Finnish estimated that finite element models are used in probably 80 percent of their designs.
- In Austria it was noted that load distribution on routine bridges using 2-D finite element method (FEM) analysis had been practiced for about 40 years. Austrian engineers specifically indicated that they model substructure and foundations as an integral part of the entire bridge model when designing integral and semi-integral bridges.
- In the United Kingdom, the standard for bridges designed for HA is an elastic grillage model, but industry is increasing its use of even more advanced analysis methods. This is being driven by improvements in software capabilities and the introduction of Eurocodes. Industry representatives said they believe that the use of more advanced analysis methods can provide significant benefit to industry, provided that designers are competent and proper QA procedures are followed, for the following reasons:
  - It allows for a more rigorous approach that provides much more accurate results.
  - British Standard Codes allow for departure from codified approach and support FEM use.
  - Eurocodes are better suited to using refined analysis methods than past national codes because Eurocodes are more performance based.
  - The use of FEM often saves clients money on initial design because future changes in design of the structure are more easily addressed. Even more money is saved on assessment and load rating of the structure because the model for this analysis is already available for use by the engineer.

FEM was developed to solve complex elasticity and structural analysis problems. Development of FEM can be traced back to the mid to late 1950s, but U.K. developers refer to roots in the development of the stress (stiffness) method by the U.S. Department of Defense at the Massachusetts Institute of Technology in the 1960s. This method became public domain in the 1970s and led to several spinoffs of 2-D modeling techniques in the late 1970s and the beginning of development of 3-D applications.

While a novelty at the time, FEM became more feasible for bridges after publication in 1974 of a book by E.C. Hambly[2] that described the underlying behavior of bridge decks and provided guidance on how structures could be analyzed using relatively simple computer models. FEM allowed detailed visualization of where structures bend or twist and indicated the distribution of stresses and

[2] Hambly, E.C. *Bridge Deck Behaviour.* ISBN: 9780419172604. Taylor & Francis Ltd, 2nd revised edition.

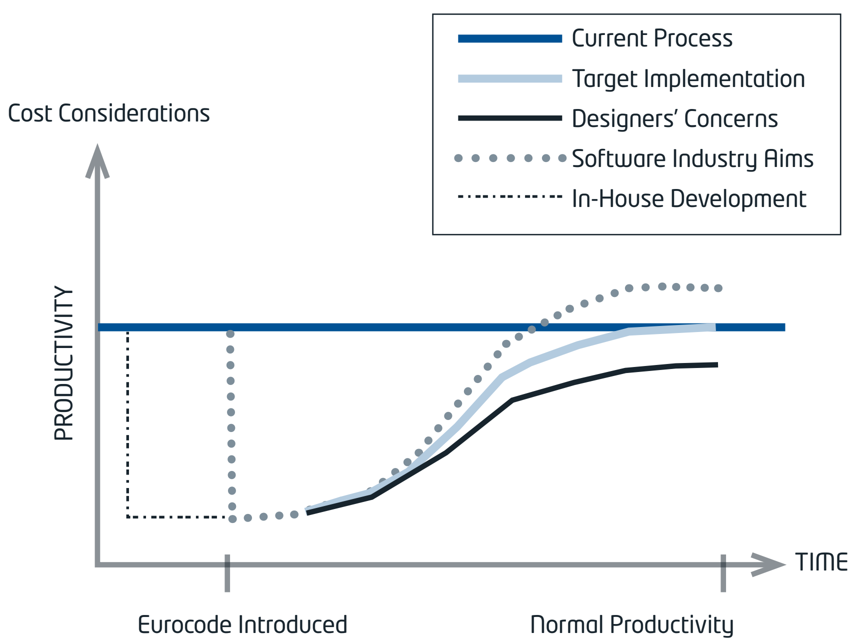


Figure 5. *Change management.*

displacements. Development was spurred by efforts of the National Aeronautics and Space Administration during the 1970s to address aeronautical and marine needs. Applications became available commercially for mainframes late in that decade. Microcomputer applications became available in the 1980s and Windows applications in the 1990s.

The conclusion the scan team reached from discussions with the agencies visited was that the initial use of advanced analysis might present a steeper learning curve, but similar levels of effort required might be achieved over time (see figure 5). Practitioners, working for the Austrian Federal Ministry for Transport, Innovation, and Technology, estimated that they could model and design a simple bridge analysis in about 40 labor-hours and generate a routine design for a two-span, 50-meter continuous prestressed concrete bridge in about 4.5 labor-months.

Finite Element Analysis of Existing Bridges

EU software developers and structural engineers agree that the analysis models developed during preliminary bridge design can be used throughout the bridge's life, from design through operations and management to decommissioning. They also pointed out that, when analyzing a bridge for load capacity, increased model sophistication, if applied correctly, provides a more accurate and often higher load-carrying capacity.

The enhanced accuracy of refined analysis can be more significant in the rating of existing bridges than in the design of new bridges. Typically, force effects from approximate methods are conservative and more uncertain compared to those from refined analysis. For example, live-load moments derived using distribution factors are typically greater in magnitude than those of refined analysis. Rating bridges using live-load and dead-load moments from refined analysis should yield higher rating factors, allowing heavier permit loads and fewer posted, rehabilitated, or reconstructed bridges. The conservatism of rating through one-dimensional analysis has a high cost in terms of rehabilitating or reconstructing bridges with potentially safe load-carrying capacities.

Unfortunately, permit-load rating of existing bridges through the application of refined analysis in the United States is limited to the allowable stress rating and load factor rating methodologies. The live-load load factors of Table 6A.4.5.4.2.1-1 of the AASHTO *Manual for Bridge Evaluation* (MBE) are applicable only to the rating of existing bridges using approximate analysis, as the table inherently requires the use of distribution factors. Thus, refined analysis cannot be used in conjunction with the LRFR methodology for permit-load rating. This limitation in the MBE permit load factors should be removed by providing guidance for use of refined analysis methods for permit load ratings.

The use of 2-D and 3-D models in evaluation calculations is common in Finland. Finnra indicated that bridge operations personnel are well educated in the use of modern analysis tools. For load-rating calculations of existing bridges, more sophisticated means are also used because more is at stake. Further, for critical bridges on the road network, load tests are performed to confirm actual structural behavior and to verify models used in calculations. Finnra indicated that its intent was to maintain bridge models as part of the bridge record over the life of the structure, updated with information of condition and repair actions for future analysis needs.

Weigh-in-Motion Data

Germany and France use WIM data to calibrate their NDP for live load factor. Germany also uses current WIM data and Monte Carlo simulations to study future traffic (figure 6).

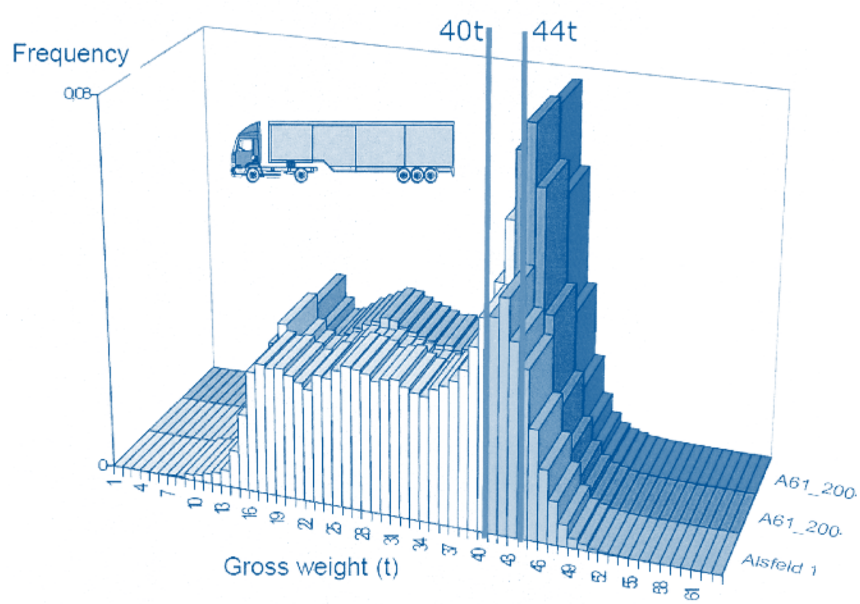


Figure 6. *Weigh-in-motion data.*

Use of Enhanced Reliability Analysis to Assess Safety

Quantification of Safety

The team's conclusion was that the countries visited quantify safety in a manner similar to the United States, but it is stated as probability of failure rather than as a reliability index, return period, or factor of safety. In general, the team found an increasing emphasis on risk analysis for both design and rating. The French allow use of reliability analysis in lieu of specifications.

Structural safety of the Eurocode, soon to be mandated for bridge design in all of the European countries visited during the scan, is quantified by a reliability index, ß, just as in the AASHTO *LRFD Bridge Design Specifications*. The Eurocode is calibrated to three levels of consequence class (CC1, CC2, and CC3) and three levels of reliability class (RC1, RC2, and RC3), as defined in table 2.

The vast majority of bridges are designed to CC2 (or RC2), with CC3 (RC3) a possibility only for bridges with very high consequences of failure, such as a signature bridge. The target annual probabilities of failure are 1.00E-06 and 1.00E-07 for CC2 and CC3, respectively. While a target reliability index is tabulated in the Eurocode for each probability of failure, the Europeans quantify safety more often as probability of failure than as a target reliability index.

In the United States, the target reliability index, $ß_T$, of the *LRFD Specifications* is about 3.5 with a corresponding probability of failure of 2 in 10,000 over the 75-year design life of the bridge. Important bridges with higher consequences of failure can be designed for higher loads by applying the load modifier of Article 1.3.5 acknowledging operational importance, $\eta_I = 1.05$. The commentary to Article 1.3.2.1 suggests that a load modifier of 1.05 results in an increased safety index of about 3.8.

The bases of the design methodologies of the Eurocode and the *LRFD Specifications* are quite similar. At first glance, each code appears to be calibrated to a different level of reliability. Careful consideration shows that these levels of safety are fairly comparable. To reach this conclusion, similar reference periods must be considered. Table 3 summarizes the probabilities of failure, P_F, inherent to the Eurocode and the *LRFD Specifications*, along

Table 2. *Eurocode consequence classes (adapted from Table (B1)–EN1990).*

Consequence Class	Description Related to Consequences	Reliability Class
CC1	Low consequence for loss of human life; economic, social, or environmental consequences small or negligible	RC1
CC2	Moderate consequence for loss of human life; economic, social, or environmental consequences considerable	RC2
CC3	Serious consequences for loss of human life or for economic, social, or environmental concerns	RC3

Table 3. *Inherent probabilities of failure (P_F) and corresponding reliability indices (ß).*

Code		Reference Period (Years)				
		1	50	75	100	120
Eurocode	CC2	**1.00E-06**	5.00E-05	7.50E-05	1.00E-04	1.20E-04
		4.75	*3.89*	*3.79*	*3.72*	*3.67*
	CC3	**1.00E-07**	5.00E-06	7.50E-06	1.00E-05	1.20E-05
		5.20	*4.42*	*4.33*	*4.26*	*4.22*
LRFD	Typical bridges	2.67E-06	1.33E-04	2.00E-04	2.67E-04	3.20E-04
		4.55	*3.65*	*3.50*	*3.46*	*3.41*
	Important bridges	9.60E-07	4.80E-05	7.20E-05	9.60E-05	1.15E-04
		4.76	*3.90*	***3.80***	*3.73*	*3.68*

with the corresponding reliability indices, *ß*, in italics. The defining probabilities of failure in the case of the Eurocode and the defining reliability indices for the *LRFD Specifications* are shown in boldface.

For an important bridge, the Eurocode has a smaller probability of failure associated with CC3 and correspondingly a higher reliability index than the *LRFD Specifications*. This observation is not surprising because the load modifier for important bridges in Article 1.3.5 was chosen rather subjectively. A load modifier greater than 1.10 would be necessary for important bridges to yield safety levels in the *LRFD Specifications* comparable to CC3 of the Eurocode.

Bridge Operations

The Eurocodes currently have no formal rating procedures or specifications for bridge rating, although development work is underway. Nevertheless, it was apparent to the scan team that assuring safe and reliable highways systemwide was a priority in all of the countries visited. These countries were willing to take additional measures to ensure service is not disrupted, as illustrated by the U.K. HA's stated objectives of "safe roads; reliable journeys; informed travelers." The team observed that one reason behind this philosophy is the apparent lack of alternate routes in European highway systems compared to the United States, which makes network resilience extremely important.

The team found that most countries have a multiple-level rating process in place that employs an increasing sophistication in analyzing traffic loads. Reliability analysis techniques may be used to rate substandard bridges. In France, a probabilistic assessment is being done to determine residual capacity in suspension cables. Risk analysis is being done of 116 multispan post-tensioned girder bridges to develop an efficient plan of surveillance. The analysis involves radiography in some cases, exposing the damage in others, curvature or cross-bow measurements, more detailed analysis, etc. The United Kingdom uses reliability-based analysis for the highest level of bridge assessment and hopes in the future to have assessment standards that reflect target reliability-based consequences of failure.

The Austrians will perform reliability analysis and accept a reduced level of safety in some cases. Nonlinear analysis is acceptable to the Austrians and can be coupled with reliability analysis to maximize remaining service life in existing structures.

Quality Assurance/Quality Control

Design Checks

In the European Union, independent bridge design checks are commonly, although not always, required. These checks are often performed by engineers not employed by the original designer and, in some cases, appointed by the owning agency to assure a full independent check of the bridge design. Usually only the site-related design data are provided and no actual design calculations are provided to the checker. Where assumptions are made, a discussion and agreement between checker and designer are conducted before the check is started. While the scan team found this was a standard practice in all countries visited, the degree to which independent checks were conducted varied from being dependent on the complexity of the work and risk to the owner (United Kingdom) to being a mandatory requirement in the national building code for all designs (Germany).

In Germany, the task of the check engineer, or Prüfingenieur, is to ensure that public safety—especially life, health, and natural conditions—is not endangered by the performance of civil structures. The use of check engineers is dictated by national building codes administered by local building authorities. In the structural engineering field, the scope of work of the check engineer is to check the structural analysis and the corresponding design, detailing, and drawings to identify any engineering errors or omissions. Specific tasks of the check engineers include assuring a positive response to the following:

- Have all of the actions, load combinations, and other influences that may affect the structure during construction and its service life been anticipated and considered?
- Are the structural models for analysis correct?
- Are the internal forces correctly calculated?
- Are the design and detailing of the members correctly done?
- Are the drawings correct?

The check engineers verify the design work of others, regardless of credentialing. The Germans referred to this level of checking as the "four-eyes principle." The check engineer is appointed directly by the owner to ensure his or her independence from the economic interests of the contractor and the design engineer. The check engineer makes a complete and independent structural analysis of the bridge and ensures that all calculations and drawings of the design engineer are free of errors.

As previously stated, standardization of software verification was not considered a necessity. Typically, it is left to the vendor. Also, design offices make efforts to conduct in-house training and establish proper technical management of the work of junior staff. Caution is exercised when integrated software is used because it can lead the engineer to a "black-box" approach, in which the data being input are not verified as accurate. Integrated software that transfers data may avoid data transfer issues that can occur when using separate analysis and design software packages, but care must be taken to ensure the original data are error free.

In general, practices in Austria vary. The Austrian national railroad agency performs design checks in-house. The Austrian national highway agency checks plans, but does not check calculations. The practice of the city of Vienna is to hire two different consultants for all but the simplest bridges, one to design the structure and a second to check the design. The city determines whether a check engineer is required, typically basing the decision on the complexity of the bridge. Austrian bridge designers are held responsible for design errors and omissions. Austrian consultants may hire an outside check engineer to check their work similar to practices in Germany, as shown in figure 7. City engineers stated that the expectation is that designers are registered engineers and, as such, are responsible for design. A checker is not needed for a small bridge. For larger bridges, an independent check is expected to be performed, but the decision appeared to be that of the designer.

Owners in Austria do not dictate the analysis procedure. Consultants may use hand calculations to check their colleagues' work. The Austrians have no formal definition of failure, but in general it is considered as not meeting the design criteria. Such failures are usually the responsibility of the designer, but an investigation, typically by a university professor, is used to determine responsibility.

Inspection

As noted in past scans, Finnra's annual certification procedure for bridge inspectors is noteworthy. Inspectors are required to perform a field inspection of a minimum of two reference bridges, and their resulting condition assessment is compared to ratings determined by Finnra staff. Consultant inspectors desiring to inspect numerous bridges annually may be required to inspect and be evaluated on as many as four reference bridges. The results of these quality control inspections are used to determine personal quality points assigned to an inspector. These quality points are used as part of Finnra's procurement process to select inspectors and to develop refresher training for inspectors when large differences from control ratings are noted (figure 8).

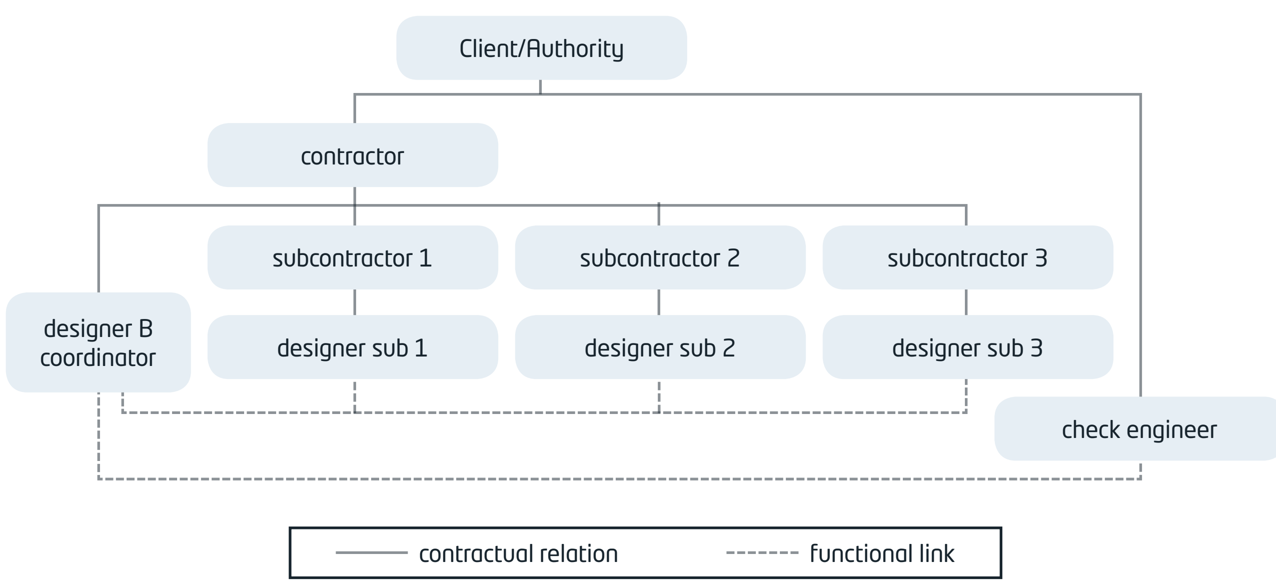


Figure 7. *Contractual relationship of the check engineer.*

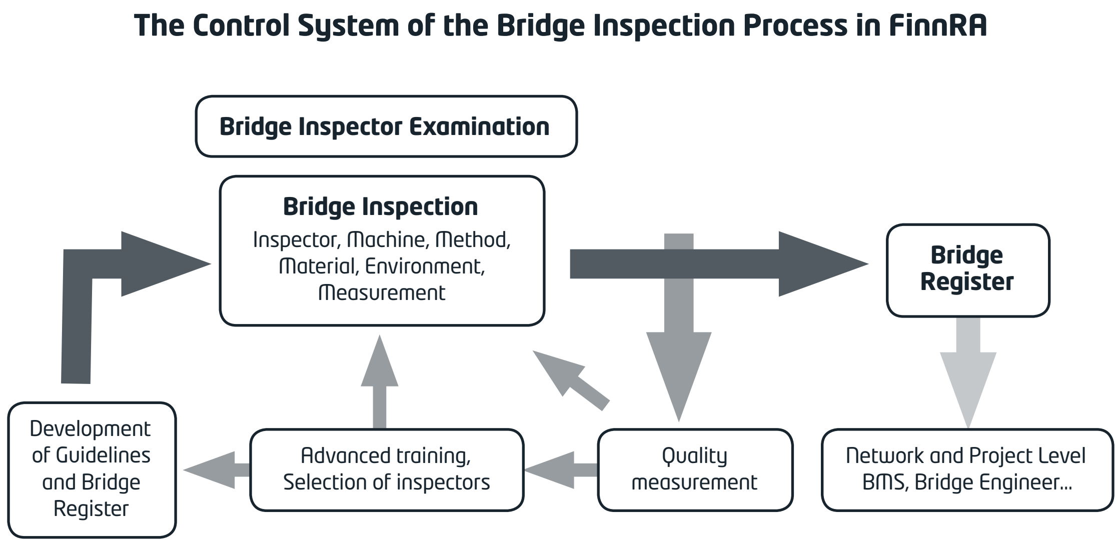


Figure 8. *Finnish statistical process control.*

Additional information on Finnish statistical process controls in the bridge inspection program is in Appendix D.

Laser Scanning

To assist in developing the models for existing structures in Finland, structures without plans are sometimes laser-scanned to determine actual dimensions. The resulting point cloud is used to establish the structures' surfaces (figure 9).

Laser-scanning techniques are also used on existing bridges to document dimensions of existing surface conditions in connection with larger repairs. Laser scanning is also used to develop as-built records for new structures. The structure is scanned at several points during construction: after the substructure construction is completed, after the superstructure formwork is erected, after reinforcement is installed, after the concrete deck slab is poured, and when construction is completed.

QA/QC in the United Kingdom

In the United Kingdom, calculations become the property of HA.

The United Kingdom also makes a special effort to study failures worldwide to determine possible preventive actions that may be required to avert similar events within its inventory. HA studies published documentation on bridge failures, reviews practices to ensure similar risks to its structures do not exist as a result of standard practices, and develops revisions to its standards should a vulnerability be identified.

The U.K. "approved in principle" process helps by requiring that the analysis method be submitted for review and acceptance along with assumptions and a description and diagram of the idealized structure before a private firm is allowed to proceed with design and analysis.

Construction compliance certificates were another method of assuring quality in the United Kingdom.

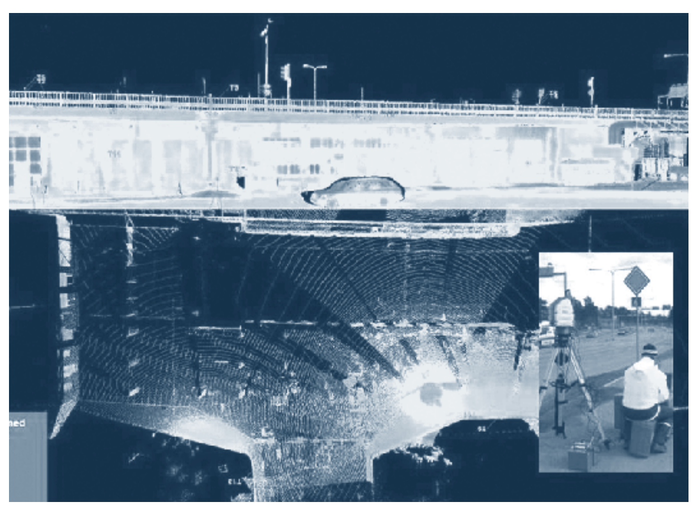


Figure 9. *Laser scanning of structures in Finland.*

Processes and Practices to Provide Serviceability and Durability

The EU agencies visited shared many practices, details, and standards that they believed contributed to durability of highway bridges in their inventory. The scan team considers the following noteworthy:

1. As reported by several previous scan teams, the use of a properly designed, installed, and maintained waterproofing membrane system has provided excellent service in all countries visited. Bare concrete decks or decks reinforced with epoxy-coated, clad, or stainless steel bars are built rarely. Waterproof membrane on concrete deck for corrosion protection with epoxy underneath to seal cracking in the young concrete is standard practice throughout Europe. The use of membrane waterproofing on integral and continuous bridges is mandatory in the United Kingdom. U.K. engineers are highly confident of the enhanced performance that membrane waterproofing can provide and do not believe that the use of membranes can be eliminated by the use of other means to waterproof concrete. The standard deck design in the United Kingdom is 8- to 10-inch (203- to 254-millimeter (mm)) thick decks with membrane waterproofing overlaid with asphalt.

2. The use of integral and semi-integral bridges is practiced in some EU countries and is very popular in two countries visited, Austria and the United Kingdom. Every effort is made to move all joints off the bridges to eliminate the damage that results from leaky joints or the need for bearings. The Austrians are so confident in the decreased rate of deterioration of integral bridge designs that they stated they have extended the interval between detailed checks (hands-on inspection) from 6 to 10 years. The Austrian details include an inclined drag plate behind the abutment (figure 10). The Austrians favor use of an inclined drag plane because in their experience it avoids the “bump at the end of the bridge” issue. Also, when the drag plate is attached to the structure, which is typically the detail used in Austria, the area where cracks may arise because of thermal effects is not directly at the bridge. This protects the structure from water penetration through possible cracks and further protects the structure itself. When a sliding drag plate (not attached to the structure) is used, Austrian engineers try to distribute the changes in length to two distinct areas: one at the end of the structure and a second at the end of the drag plate. Thus, the total elongation is taken by two distinct areas where cuts in the pavement are provided to prevent uncontrolled cracking. Austrian engineers use the total length of the drag plate to distribute the thermal effects. In doing so, they hope to eliminate the need for providing expansion joints at any location in the pavement. Austrian engineers believe that the use of either horizontal or inclined drag plates greatly reduces issues normally encountered in transitioning from the roadway section to the bridge deck.

3. The German method of calculating minimum reinforcement to prevent brittle failure was of interest because of issues with similar provisions in the AASHTO LRFD specifications.

4. Allowable stresses were noted in the various countries visited because the design values play a role in serviceability.

Processes and Practices to Provide Serviceability and Durability

The main items to provide a sufficient service life are the following:

1. Density, quality, and thickness of concrete cover (for corrosion protection of steel bars)
2. Crack control (for corrosion protection of steel bars)
3. Stress limitation (for concrete and steel bars)
4. Appropriate detailing of the reinforcement
5. Appropriate detailing of the bridge to limit external attacks (waterproofing layer, waterspouts, sufficient cross and longitudinal slope)
6. Taking into account the evolution of material properties during the prescripted lifetime of the bridge: concrete (shrinkage, creep), prestressing (stress relaxation, prestress loss)
7. Precautions and recommendations to avoid alkali-aggregate reaction in concrete and delayed ettringite formation (internal sulfate attack) (type of aggregate, temperature of the concrete)
8. Avoidance of abrasion and erosion with coated macadam
9. Checking of the fatigue behavior of prestressed tendons when concrete is in tension under frequent live loads (partially prestressed structures)

SOURCE: PASCAL CHARLES, CENTRE TECHNIQUE DES OUVRAGES D’ART

5. In Germany, the allowable tensile stresses of concrete bridges under service conditions are zero. In general, the limit state of decompression must be fulfilled at the edge of a section under the quasi-permanent combination:

$$\sigma c,perm = 0$$

quasi-permanent combination (perm):

$$Ed = E\{ Gk,j \; ; Pk \; ; \psi 2,i \cdot Qk,i \}$$

Gk,j self-weight loads
Pk prestressing action
Qk variable actions
$\psi 2 = 0.2$ traffic loads on bridges
$\psi 2 = 0.5$ thermal actions

All actions are characteristic values with partial factors E = 1.0. Partial factors are basic indicators, which determine structural dimensions in relation to loading. The probabilistic assessment of reliability is performed as a parametric study in the first part of the numerical analysis. The probability of failure is analyzed in dependence on values of partial factors of material, permanent loading, and long-time variable loading. Partial safety factors are considered fuzzy numbers.

Under the state of construction the allowable tensile stress for bridges with bonded tendons is 85 percent of the characteristic tensile strength fctk;0.05 of the concrete (5 percent–quantile):

$$\sigma c \leq 0.85 \cdot fctk;0.05$$

For concrete bridges with unbonded tendons only significant higher values are allowed (4.0 up to 6.5MN/m²).

In Austria, the allowable stresses must not exceed 0.6fck or exposure classes XD (exposure to chlorides other than seawater), XF (exposure to freezing), and XS (exposure to seawater) under their normal load combination. To avoid nonlinear and excessive creep deformations under the quasi-permanent combinations, the allowable stresses must not exceed 0.45fck. For the reinforcement under the normal load combination, the allowable stresses must not exceed 0.8fyk to avoid plastic deformation and large cracks. These requirements are also valid for reinforced bridges, but normally are not relevant because the ultimate limit states govern. For post-tensioned, prestressed concrete bridges these rules might be crucial. In general, crack widths for reinforced concrete shall not exceed 0.3 mm, but this depends on the exposure class. For

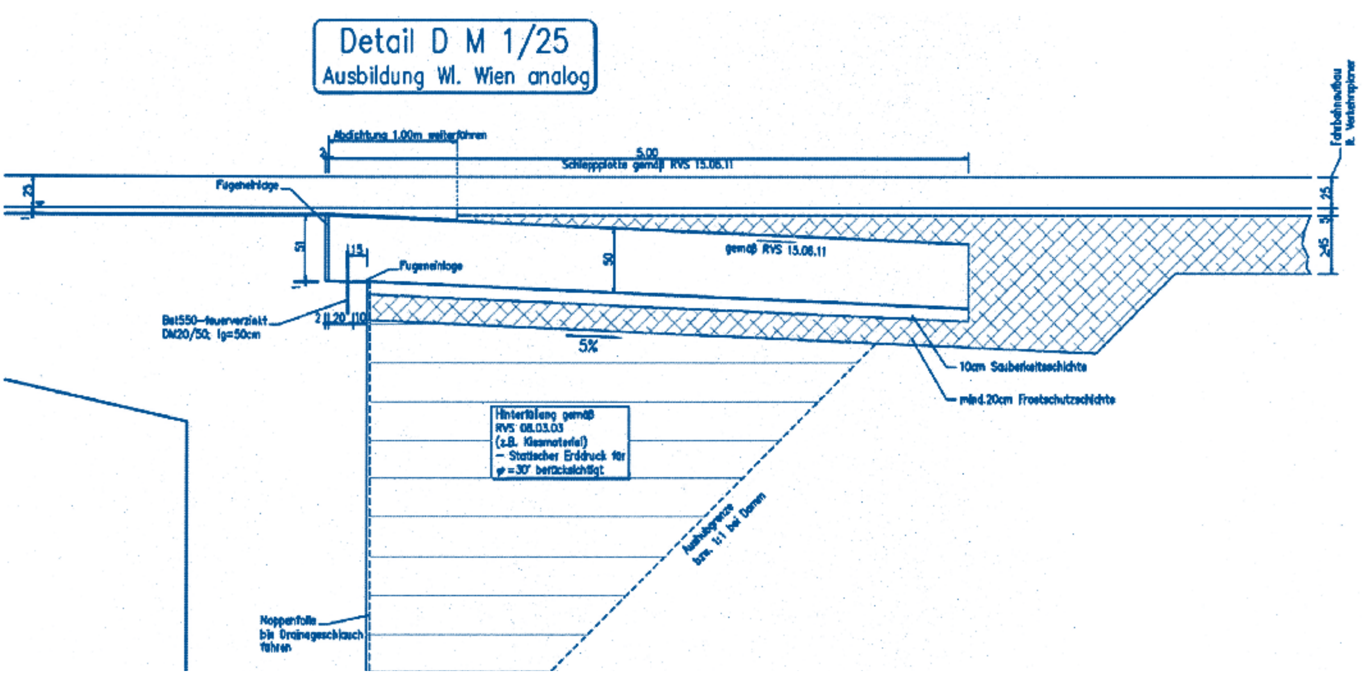


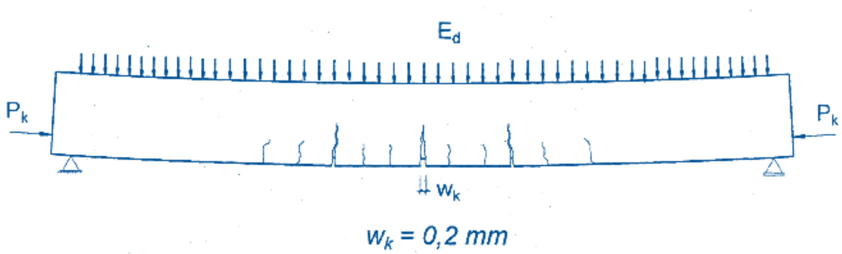
Figure 10. *Detail of drag plate used in Austrian integral bridges.*

post-tensioned, prestressed concrete, crack width depends on exposure class and type of post-tensioning and prestressing.

The French limit compression to 0.6fck for DL+LL and 0.45fck for DL only. They limit crack width to 0.3 to 0.4 mm under full live load for reinforced concrete and to 0.2 mm under full live load.

6. The German design code, DIN-Fachbericht 102, requires that an appropriate amount of reinforcing steel be provided to limit the crack width to 0.2 mm (figure 11). The Austrians generally limit their crack widths to 0.3 mm. The French permit 0.3 mm for conventional reinforcement, 0.2 mm for conventional reinforcement in a salt environment, and 0.0 mm for prestressed members in a salt environment. The Finns permit 0.35 mm and 0.40 mm for conventionally reinforced bridges for typical and routine permit trucks, respectively, and 0.15 mm and 0.20 mm for post-tensioned bridges, again for typical and routine permit trucks, respectively. The United Kingdom, on the other hand, saw no correlation between durability and cracks of reasonable widths.

7. The various concrete cover requirements were also of interest. The Germans gave consideration to the location of the element on the bridge, what environment the concrete was in, and whether the bridge carried road or rail traffic. Similar requirements were noted in France, where the cover thickness is calculated through a process that takes into account parameters such as exposure class, concrete, and diameter of the bars. The values for cover do not vary considerably from those set by AASHTO. The scan team noted that at one construction site it visited, the cast-in-place workmanship was outstanding.



wk= 0.2 mm

Figure 11. *Crack width control.*

8. The use of continuous structures and external post-tensioning were preferred in most countries visited (figure 12). The following were given as reasons given for this preference:
   - Ease of concreting without tendons in the webs
   - Improved quality of fabrication
   - Ease of inspecting and maintaining the tendons
   - Ease of replacing the tendons
   - Ease of retensioning the tendons if provided for in the design
   - Better corrosion protection (from deicing salts)
   - No effect from fatigue on the tendons
   - Reduction in web thickness, reducing dead load

   Integral continuous bridges are mandatory in the United Kingdom.

9. The Austrians presented an integrated asset management system that supports bridge management decisionmaking from the planning stages through decommissioning and demolition. The system also provides safety triggers that advise when critical issues need to be addressed to ensure the desired service life is met. Triggers are established for bridges and roadways based on a predetermined condition rating for the facility. Triggers are also established to prompt actions on noise barriers and highway intersections based on performance. The asset management program has been used by the Austrian motorway operator ASFiNAG and the Federal Ministry for Transport, Innovation, and Technology for several years. In their opinion, it is very successful, and it is consistently updated to reflect actual owner experience to provide more accurate results.

10. Two-girder bridges were commonly used because of their cost-effectiveness (figure 13). Conservative fatigue design (similar to that in the United States), high welding quality and inspection, and higher toughness steels (similar to U.S. high-performance steels) in France and the United Kingdom provided owners with confidence in this type of bridge. Austria has no regulations on redundancy or fracture criticality. Its position is that with the use of properly designed and constructed waterproofing membranes, the superstructure will last the entire life of the bridge and deck replacement will not be an issue. Two-girder bridges are

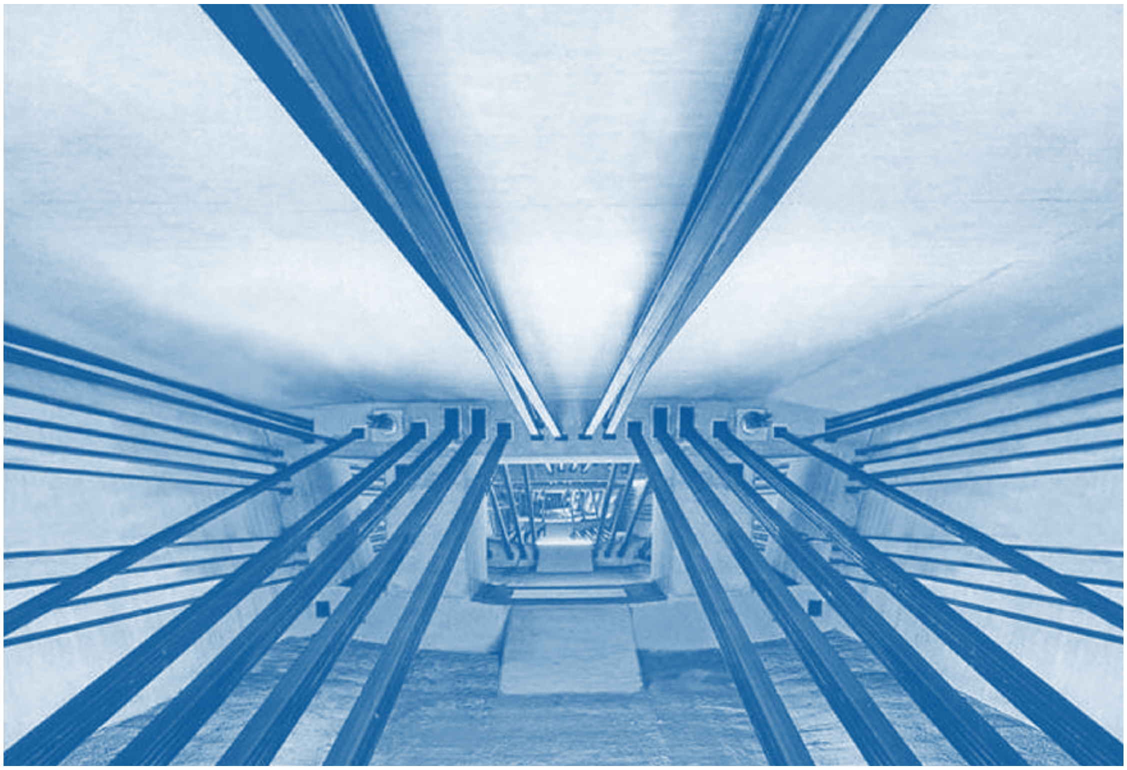


Figure 12. *External post-tensioning.*

Figure 13. *Typical two-girder system in Europe.*

routinely built in France. The French believe that this type of bridge is very competitive in the 18-to19-meter span range.

11. Emphasis was placed on using nondestructive evaluation (NDE) techniques to detect wire breakage and reinforcement corrosion.

12. The Austrians provided the following reasons for instrumenting and monitoring bridges:
    - As a means of postconstruction quality control
    - To monitor for traffic incidents or other natural or manmade events
    - To monitor for security or vandalism
    - To monitor and guide permitted or illegal loads
    - To continuously gather reliable performance data on bridge structures for maintenance and management decisionmaking
    - To provide a variety of information to designers on the behavior of a bridge
    - To gather information on the characteristics of vehicles using a bridge (e.g., types, weights, axel loads, and speeds)

13. Health monitoring was used in the countries visited more for bridge maintenance, compared with the United States where it is perhaps more of an academic exercise.

    Finnra staff members stated they believe that monitoring programs are of value not only to provide data for immediate needs, but also to provide data for future evaluation needs. Finnra believes that reliable monitoring sensors and measuring devices are already available to instrument bridges and that the price of sensors and measuring devices is quite low. The agency's experience is that the greatest cost is in maintaining the measuring devices and storing and processing data. Finnra also recognizes the use of monitoring devices for emergency alerts and to control the quality of the work and materials. Finnra recognizes that it is not necessary to instrument all bridges. It focuses on special bridges, such as long-span bridges and new types of bridges with which it has limited experience. It also uses instrumentation to study bridges with a history of issues.

    Finnra has installed monitoring systems on several new bridge projects. Officials noted that the power supply and cable conduits must be included in the design plans because sensors such as strain gauges on bar reinforcement and optical fibers must be installed before concrete is cast.

    Finnra sees a future in instrumenting bridges to provide data for asset management purposes, provide better data on long-term structural behavior and reliability, and refine life-cycle models it uses for its bridge inventory.

14. In France, permanent instrumentation may be installed for surveillance of bridges with significant deficiencies and reduced load-carrying capabilities. When significant deficiencies are noted, the local bridge manager may determine that increased levels of monitoring are warranted. This increased monitoring, or enhanced surveillance, is designed to evaluate the consequences of further damage to the structure. When the deficiencies recorded on a bridge appear likely to affect safety, the manager may require even more intense monitoring, referred to as safety monitoring. The load-carrying capacity of the bridge is evaluated to check or limit the acceptable level of traffic and to alert the manager of potential danger. When either type of monitoring is employed, the bridge is usually under permanent instrumentation. For safety monitoring, the data are transmitted continuously to a remote location. Examples of this are the Merlebach and Aquitaine suspension bridges, which have been put under permanent sound monitoring to alert French authorities of wire breaks within the cables.

15. Bridge load testing has been practiced in Finland since the 1950s, but it has become less popular in the past 20 years. Finnra required load testing on 1950s bridges designed for a lower live load (40 tons). Finnra uses load tests to determine the load-carrying capacity and need for strengthening existing bridges, study the influence of strengthening performed, verify the structural behavior of new bridges, and study the structural behavior of different bridge types. The data obtained are also used to supplement the results from computational methods and calibrate the calculation models used for analysis.

    Finnra has performed load tests to failure on six different types of bridges:
    - Two reinforced concrete girder bridges
    - One reinforced concrete slab bridge

- Two steel girder bridges with concrete decks
- One timber bridge

These tests were performed to determine structural behavior and capacity in the ultimate limit state, observe the failure sequence, and determine the distribution of forces during failure. The test was performed by loading the bridge using hydraulic jacks supported by a loading frame.

Finnra's experiences with conducting bridge load tests were positive. It concluded the following:

- In many cases "hidden" safety could be identified, allowing permitting of higher traffic loads.
- Better determination of the risk of damage can be determined by taking measurements of critical details.
- Actual load-carrying capacity can be determined, providing better results than calculations only.
- In some cases expensive strengthening or rehabilitation of a bridge can be avoided.
- Valuable data on the behavior of different bridge types and their elements have been gathered to develop better analysis methods.

Austria uses bridge load testing, but limits it to problematic bridges (about two per year) in potential need of strengthening or where trucks need to be permitted for travel.

16. Bridge weigh-in-motion (B-WIM) was reported on in Austria and France. B-WIM differs from WIM in that the bridge is used as a scale by measuring strains. B-WIM was the subject of a past European scan. B-WIM can improve on codified values for dynamic load allowance, but is limited to integral bridge types. The French are doing field tests and hope to use it more in the future.

17. WIM is used for law enforcement in the United Kingdom in conjunction with a camera. The French hope to do the same.

CHAPTER 3

Recommendations and Implementation Activities

Recommendations

Based on its findings during the scanning study, the team recommends the following:

1. Develop a nationally accepted strategy for promoting and increasing practicing bridge engineers' use of refined analysis. The team believes such a strategy would improve uniformity and consistency in design and analysis across transportation agencies, improve mobility, and expand commerce on the highway bridge network. The strategic plan should address training, perhaps through development of a National Highway Institute training course, to provide background on grillage and finite element modeling methods available for analysis of highway bridges. The strategic plan might also entail developing standardized curricula that universities can offer as graduate-level and continuing education courses throughout the United States. The strategy must also include partnering with the software industry to ensure that supporting tools become available with integration of computer-aided design and drafting (CADD) systems for both rating and design.

2. States should be encouraged by entities other than the software industry to use refined analysis (properly checked and verified) and reliability assessment as a measure to avoid posting, rehabilitating, or replacing bridge structures that affect commerce, schools, and the traveling public. Advanced tools, techniques, and training need to be developed and provided for design engineers so they can more accurately predict structural system behavior on a routine basis. Better predictions of system capacity will lead to more accurate predictions of load capacity and reduce the number of posted bridges, increasing mobility and commerce. The AASHTO *Manual for Bridge Evaluation* should introduce structural safety assessment levels in which each additional assessment level adds increasing sophistication with the objective of assessing the safety of a bridge more accurately, commensurate with risk and the need to verify adequate capacity.

3. The AASHTO Subcommittee on Bridges and Structures should consider adopting the concept of annual probability of failure (exceedance) as the quantification of safety in its probability-based design and rating specifications rather than the reliability index for a 75-year design life. Probability of failure is a more intuitive measure of safety than the reliability index. Also, annual probability of failure, instead of the probability of failure during the 75-year design life, would put the risk due to the strength limit state force effects in a format comparable to the extreme event limit states, which are typically quantified by annual probability of failure. In other words, the reference period in the table would be 1 year. The specification of a 1-year reference period, or annual probability of failure, is standard practice in other probability-based specifications, such as the Eurocode.

4. A synthesis project should be initiated to develop the basis to systematically introduce increasing levels of sophistication into analysis, load models, and reliability assessments with the objective of assessing bridges more accurately.

5. Owners should periodically and routinely reassess traffic highway loading to ensure that the AASHTO *LRFD Bridge Designs* specification design load model adequately provides for bridge safety and serviceability for a 75-year service life or greater.

6. The AASHTO Subcommittee on Bridges and Structures should consider requiring States to develop an overweight permit design vehicle for the Strength II load combination, the load combination meant to consider special permit truck loads during

the design of a bridge, particularly in high-load corridors. This is to avoid design and construction of structures that do not rate.

7. Develop and maintain a database of bridge failures domestically and internationally that provides detailed information and data on the causes of failure. A protocol should be established to initiate necessary actions owners and code-writing bodies should take to ensure that bridge design guidance addresses these failures.

8. Continue efforts to develop guidelines and training for proper use of NDE techniques to detect corrosion and breakage of cables of cable-supported bridges. Identify or develop new NDE technologies to actually quantify the amount and severity of corrosion and breakage in hidden elements (prestressing strands, ducted cables, mild steel reinforcement, etc.).

9. Independent check engineering and check engineer certification should be explored for the purpose of augmenting QA/QC processes and practices already in place for bridge designs and analyses.

10. Initiate the investigation and possible technology transfer of selected best practices and emerging technologies identified during the scan. Potential candidates include the following:
    - Development of an integrated bridge asset management process from planning through decommissioning and demolition
    - Development of guidance on the use of waterproofing membranes and asphalt overlays
    - Expansion of the use of continuous concrete box girders with external post-tensioning for new bridges and retrofit and repair of existing structures using external post-tensioning
    - Use of drag plates in the design of integral abutment bridges, as practiced in Austria

Implementation Activities

In summary, the scan team found many similarities, as well as significant differences, between the United States and the host countries in bridge design and analysis practices and bridge management and operating procedures. The team identified several key findings that it considers best practices, outlined in this report. The team believes that the best practices should be mainstreamed into practice in the United States by making the information available on Web sites, seeking demonstration or pilot projects, and holding workshops in association with the pilot projects. In addition, the team has planned papers and presentations at national and local meetings and conferences over the next several years. The purpose of the papers and presentations is to describe the overall results of the scanning study and details of specific technologies that participants should consider implementing in their States.

The results of this scan will support ongoing activities by FHWA, the AASHTO Subcommittee on Highway Bridges and Structures, and TRB/NCHRP to improve U.S. bridge design and analysis codes and specifications. This scan report contains many detailed findings that will enhance U.S. understanding of bridge design safety and serviceability and will lead to pursuit of further practices that will improve bridge design, analysis, and operations nationwide. The scan team is convinced that implementing the key findings of this study will improve design and operational safety standards of U.S. bridges, enabling them to provide longer service life with less maintenance. Changes to the bridge design and analysis codes will provide operational improvements that will increase mobility and help preserve the Nation's highways.

A Possible Approach to Risk-Based Assessment and Prioritization of Existing Bridges

Risk evaluation considers the likelihood and consequences of failure. Bridge safety is measured in terms of the risk level rather than the conventional failure probability level. In assessing risk to public safety, relevant factors such as the consequence of failure, structural system, indications of distress, possibility of hidden distress, bridge hits, extreme event data, traffic load history of the structure, and level of previous assessments completed should all be taken into account. Standards should provide guidance on appropriate inspections, safety assessment measures (load ratings, fatigue), intermediate mitigation measures (load posting, monitoring), and long-term strengthening or replacement strategies that may be used to manage the risks associated with structures.

The decision to take interim measures should be based on an assessment of the risks associated with the continued use of the structure without imposing any interim measures. The strengthening or replacement of all substandard structures is an ongoing process, and the work needs to be prioritized. Prioritization of strengthening or replacement should take into account the relative risk of each structure to public safety. A further enhancement would be to adopt a whole-life risk approach to maintain an acceptable level of risk over the life cycle of the bridge.

Of specific interest to scan team members was information the European hosts provided on assessment and prioritization of their existing bridge stock. The following is derived and combined from countries visited during the scan and attempts to capture their best practices in bridge assessment. It is described as an implementable process that includes several worthwhile concepts instead of presented as stand-alone ideas. This will be an iterative process.

Levels of Assessment Concept

Assessment of an existing structure should be carried out in stages of increasing complexity tied to the level of risk associated with the structure and with the objective of efficiently determining its adequacy. Early stages may contain conservative means of evaluating force effects. Provided that a structure is shown to be adequate at early stages, no further analysis is required. However, if a structure is found to be inadequate at an early stage and is considered to pose an unacceptable level of risk, assessment work should continue and later stages should seek to remove any conservatism in the assessment calculations.

The levels of assessment introduce increasing sophistication with the objective of assessing the safety of a bridge more accurately.

Each additional level of assessment may involve considerably more time and cost. The bridge owner should consider these implications and approve the progress of the assessment through the various levels.

LEVEL 1

Level 1 is the simplest level of assessment, based on a conservative estimate of load capacity. At this stage, only simple analysis methods are necessary.

LEVEL 2

Level 2 assessment involves the use of more refined analysis and better structural idealization. More refined analysis may include grillage or finite element analyses whenever these may result in more accurate capacities. Nonlinear and plastic methods of analysis may also be used for the substructure; actual measured material properties may be used for the superstructure.

LEVEL 3

Level 3 assessment includes the option to use bridge-specific live loading. Recent WIM data could be used to characterize truck load models (or calibrate load factors) specific to the site. Use of bridge WIM systems should be investigated on small structures because more accurate dynamic amplification factors can be obtained. Level 3 assessment may use material testing to determine characteristic strength or yield stress.

LEVEL 4

In Level 4 assessment, probability-based system methods are used in conjunction with an owner-specified level of safety. Such methods require in-depth knowledge of and expertise in reliability analysis techniques. (Levels 1 through 3 account only for element failures in bridge assessment. However, in many cases, element failures may not cause system failures. In other words, a bridge may have a smaller chance of failure than the corresponding system value.) A technical approval process should be implemented for the owner and assessment team to concur

(continued)

A Possible Approach to Risk-Based Assessment and Prioritization of Existing Bridges *(continued)*

on the method of analysis and how the uncertainties of the specific bridge condition and the local traffic situation are considered. Structures believed to pose an immediate or high risk to the public may be candidates for a Level 4 assessment.

NOTE: In Level 1 and 2 assessments, extremes of normal traffic are represented by notional load models. Site-specific load models are used for Level 3 and 4 assessments.

NOTE: Traffic WIM data can be obtained by mounting sensors in the road pavement or on an existing bridge structure and estimating the corresponding static loads using appropriate algorithms. It is clearly desirable to collect as much data as possible, but 1 or 2 weeks of continuously recorded data may be sufficient for assessment purposes. It is important to ensure that these data are representative, so consideration should be given to seasonal variation patterns when scheduling a measurement period. The COST (European Cooperation in Science and Technology) 345 report does not specify the required accuracy of WIM data. However, some guidance is given by specifying the required accuracy with reference to the COST 323 WIM specification. Bridge loading is not overly sensitive to WIM system accuracy, and a system with accuracy that corresponds to about 95 percent of gross vehicle weights within 15 percent of the exact static value is considered sufficient. Extreme value distributions, such as those contained in the Gumbel family, are fitted to measured data recorded over a period of time. Subsequent extrapolation of these fitted distributions for a specified return period yields the characteristic value.

NOTE: Level 1 to 3 assessments, as described, are based on code-implicit safety levels, incorporating the nominal values of loads and resistance parameters and the corresponding load and resistance safety factors. To ensure that the assessment rules are simple for routine use, the format and values of the load and resistance factors are chosen to accommodate a wide range of structure and component types. Level 4 is a departure from these sometimes conservative assessment techniques.

APPENDIX A Amplifying Questions

Safety and Serviceability—Design and Construction

Quantification of Safety

In the United States, structural safety is measured through a reliability-based uniform safety index (reliability index) for individual structural members and is based on live load data (frequencies and weights). In current design specifications, the index is selected on an average value of reliability indices of existing bridges, not on a desired level of safety. The reliability index is achieved by specifying calibrated load amplification factors and capacity reduction factors. Neither the live load data nor the reliability index has been revisited since the development of the present specifications.

- What is the philosophical basis of safety for your design and evaluation requirements for bridges, including superstructure, substructure, and foundation (e.g., working stress; uncalibrated partial factors; reliability theory expressed through calibrated partial factors, a target reliability index, annual probability of failure, or other means)?
- How do you define bridge failure? Have you had any failures of bridges due to overload?
- Are your safety measures element or system based?
- How (why) did you determine to use those measures?
- How do you quantify those measures?
- How do you maintain your measures? Do you consider future increases in vehicular volume and weight and deterioration of components? If so, how?
- Are your measures different for different routes, sizes, or types of bridges or specific bridge components?
- Have weigh-in-motion data been used to develop your design specifications and, if so, how?
- What are your current design live loads and how were they developed?
- Do you use a different live load model on your longer span bridges (cable-stay, arch, or suspension bridges)?
- Do you consider the probability of multiple heavy trucks being on your bridges simultaneously (side-by-side trucks, not all trucks being fully loaded, or caravan of trucks)?
- Please describe your current and planned efforts to support future advances in quantifying and assuring safety and service life through proper design codes.
- What are your quality assurance and quality control (QA/QC) procedures for bridge analysis and design? Are they published?
- Do you have published guidelines for bridge capacity evaluation QA/QC?
- What are your procedures for detecting and/or preventing design errors? Do you have bridge design firm QC procedures for designing bridges, and owner/agency procedures for reviewing and approving bridge design plans and calculations?

Serviceability

In the United States, serviceability considers deformation, cracking, and stress limits of components. These criteria are based on past practices. Serviceability criteria are intended to give 75 years of service life, but the criteria used are not based on scientific evidence or research.

- How do you define bridge serviceability and service life?
- What are your performance measures for serviceability?
- What are your goals for bridge service life?
- What design checks and measures have you taken in the design of new bridges to achieve this performance?
- Are live load deflection, vibration, or resonance limits a consideration?
- Do you check bridges for fatigue?

Safety and Serviceability—Operations

In the United States, structural safety of existing bridges is measured through two uniform safety indices for individual structural members that are based on live load data and the structural condition of members. Load capacity evaluations can be done at a higher national screening level (inventory level) or a local screening level (operating level). The index for the national inventory level is based on the design level of safety. The local operating level is based on a lower level of safety determined by the local jurisdiction's experience with its existing bridges through smaller live load amplification factors.

Laws and Regulations Governing In-Service Bridges

- Are there laws governing the maximum legal load on bridges, and is the maximum legal load different from your design and evaluation vehicles?
- Have you had or do you predict any increase in legal truck weights? If so, how do you assess the state of your bridge inventory to support the legal load increase?
- How do you enforce that loads crossing your bridges do not exceed the safe load capacity of the structure?
- Which agency (and at what level of government) is responsible for approving overload permits? What is its review and approval process?

Load-Carrying Assessment (Evaluation and Rating) of Bridges

- What initiates the evaluation process (e.g., initial design, deterioration of the bridge, change in legal load, operating load, specification changes)?
- Do you have a separate unit to perform bridge assessment, or do you use the design unit to perform assessments?
- In evaluating a bridge, do you evaluate the entire bridge system (all members, connections, bearings, substructures, including foundations), or do you evaluate a limited number of elements?
- What are the serviceability checks when evaluating existing bridges?
- Do you use the same or different safety factors (load and resistance factors) for the design of new bridges and evaluation of existing bridges, and does it vary depending on the type of bridge?
- Do you use load testing (full-scale field testing) to check bridge safety? If so, what are the criteria for selecting a bridge for load testing?
- How often do you use permanent instrumentation of bridges for assessment? Why?
- Do you have bridges with elements of unknown structural capacity (no plans or records) and, if so, how do you evaluate their load-carrying capacity?
- What are your procedures for restricting trucks from crossing a bridge with diminished load-carrying capacity? What are your practices for putting up signs with load restrictions?
- Do you restrict loads on a bridge because of serviceability issues in addition to safety? Please elaborate.
- Do you permit trucks heavier than the legal load limit to cross bridges and, if so, how are operations of these vehicles controlled (escorts, route restrictions, vehicle speed, etc.)?
- What level of structural analysis do you use to evaluate posting and permitting of bridges? Do you base the evaluation on certain elements or the entire bridge (including foundations)?
- In evaluations of legal loads and overweight vehicles, what combinations of possible loads are considered (e.g., live load, wind, braking forces)?

Record Keeping

- Do you maintain electronic records (analytical software files as well as bridge plans) for use in future evaluations?
- What records are kept during construction and how are they used during the life of the bridge? For example, is a baseline chloride measurement taken to assess service life of the bridge deck?

Refined Analysis—Design, Construction, and Operations

In the United States, bridge code longitudinal effects are uncoupled from transverse effects using empirical formulas for live load distribution. This uncoupling process allows simplified analysis of single members or sections. For complex bridges refined analysis (grillage and finite element analysis) may be used.

Guidelines

- To what extent is simplified analysis of single members used for design and/or evaluation?
- Do you use refined analysis in your evaluation and design (grid or three-dimensional analysis)?
- Do you consider the accuracy of your analysis technique in the design and evaluation of your bridge? If so, how?
- Do you have guidelines for bridge modeling and performing structural analysis to assure the production of efficient designs while minimizing iteration? If so, what are they?
- Do consultants need to obtain special permission from the bridge owner before performing a refined analysis? Do you specify the software for the designer

(consultant) to use when performing a refined analysis?

- How do you verify the results of the refined analysis in terms of modeling and output to ensure that the results are valid?
- What software is allowed for bridge analysis and design? How is it validated and accepted for use?
- What information does the software developer provide to assure that the design engineer understands how the analysis is being done and how any design recommendations were arrived at?
- Describe the educational background of the design/analysis software user.
- Do you use nonlinear analysis? If so, when?

Research and Development

- Please describe your current and anticipated future efforts to support any advances in refined analysis.
- Please describe your current and anticipated future efforts to support advances in quantifying and assuring safety through proper evaluation guidelines.
- Please describe your current and anticipated future efforts to support advances in quantifying and assuring service life through proper evaluation guidelines.

APPENDIX B
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Harry A. Capers, Jr. (report facilitator) is vice president and corporate bridge engineer for Arora and Associates, P.C., a regional transportation engineering firm in the northeastern United States. He is responsible for oversight of all highway bridge work in the firm's six offices. He also manages several initiatives with various universities conducting research on bridge topics and is the principal investigator for the NCHRP 20-68A Project, "U.S. Domestic Scan Program." In addition, he is the firm's quality assurance manager. He chairs TRB Committee AFF10 on

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Gregory L. Bailey is the director of the Engineering Division for the West Virginia Division of Highways (DOH) in Charleston, WV. He is responsible for developing and implementing statewide policies and procedures for bridge design and structural design issues used in DOH programs. He also has a consultative role in developing evaluation and rating policies and procedures. Bailey has served with the DOH for more than 16 years and has more than 31 years of experience in structural and bridge engineering for State highway administrations, local government entities, and private engineering firms. He has a bachelor's degree in civil engineering from West Virginia Institute of Technology and a master's degree in civil engineering (structural emphasis) from Virginia Polytechnic Institute and State University. He is a licensed professional engineer in West Virginia and serves as the DOH voting representative on the AASHTO Subcommittee on Bridges and Structures. He is chair of the T-16 Timber Structures Committee and vice chair of the T-5 Loads and Load Distribution Committee.

Ian M. Friedland is technical director of bridge and structures research and development for FHWA's Turner-Fairbank Highway Research Center in McLean, VA. Friedland provides national leadership and expert technical advice on developing and delivering new technologies in bridge engineering to FHWA field offices and State transportation agencies. Before joining FHWA, Friedland was associate director for development with the Applied Technology Council. Before that, he was assistant director for transportation research at the Multidisciplinary Center for Earthquake Engineering Research and a senior program officer with TRB, in charge of all bridge research conducted in the AASHTO-sponsored NCHRP. During his tenure with NCHRP, a number of major bridge initiatives were completed for AASHTO, including the development of the *LRFD Bridge Design Specifications, Manual for Condition Evaluation of Bridges, Guidelines for Bridge Management Systems,* and *Guide to Metric Conversion.* He has been a member of numerous national task forces and advisory committees, including those responsible for developing Pontis and BRIDGIT bridge management system software. Friedland is a registered professional engineer and is a member of ASCE, the Earthquake Engineering Research Institute, and TRB. He serves on the Executive Committee of the ASCE Technical Council on Lifeline Earthquake Engineering and as associate editor of the ASCE *Bridge Engineering Journal.* Friedland received a bachelor's degree in civil engineering from Cornell University and a master's degree in structural engineering and structural mechanics from the University of Maryland.

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Dr. Dennis R. Mertz is a professor of civil engineering at the University of Delaware (UD). He is the director of UD's Center for Innovative Bridge Engineering. The study of bridge-design methodologies and particularly the strength and service limit states are prominent among Mertz's research activities. As co-principal investigator of NCHRP Project 12-33, he was one of the authors of the first edition of the AASHTO *LRFD Bridge Design Specifications*. As a consultant to the bridge-design firm Modjeski and Masters (where he was an associate before coming to UD), he has continued to author annual interim changes to the *LRFD Specifications*. All three of Mertz's civil engineering degrees are from Lehigh University. He is a registered professional engineer in Pennsylvania.

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Thomas Saad is a structural design engineer in the FHWA Resource Center in Chicago, IL. Saad is responsible for developing and delivering products and services to aid State highway agencies nationwide in implementing load and resistance factor design and rating. He is also responsible for delivering programs to help State highway agencies implement high-performance materials and accelerated bridge construction technologies. Before joining the FHWA Resource Center, he served as the Indiana Division bridge engineer and as a bridge engineer in Connecticut, Georgia, Louisiana, and Missouri. Saad graduated from Michigan State University and has a master's degree in civil engineering from the Georgia Institute of Technology. He is a licensed professional engineer in Indiana and serves on the AASHTO Technical Committee for Loads and Load Distribution and the AASHTO BridgeWare Virtis-Opis Task Force.

Bala Sivakumar is vice president and director of special bridge projects for HNTB Corporation in New York. Sivakumar's professional practice areas include weigh-in-motion studies, site-specific load modeling, finite element modeling and advanced structural analysis applied to fatigue and fractures investigations, forensic investigations, seismic analysis and retrofit, load rating, and load testing. Sivakumar was the architect of the load and resistance factor rating (LRFR) evaluation philosophy and was the primary author of the AASHTO *LRFR Manual* (2003) and the new AASHTO *Manual for Bridge Evaluation* (2008). He served as the principal investigator of NCHRP Project 12-63 initiated in 2003 to propose revisions to AASHTO's legal loads and loads for posting of bridges. Five new legal load models developed under this project were adopted by AASHTO as new national posting loads in 2005. He was the principal investigator for NCHRP 12-76 for TRB to develop protocols for collecting and using weigh-in-motion data for developing national design load models for the AASHTO *LRFD Bridge Design Specifications*. He has provided training seminars on LRFR to 15 State DOTs and LRFR implementation assistance to several States under an FHWA contract. He served as the principal investigator for the Wisconsin Department of Transportation for the forensic investigation of the Hoan Bridge failure in Milwaukee. He also served as an investigator for the Minnesota Department of Transportation for the I-35W bridge collapse in Minneapolis. He conducts a 2-day LRFD bridge design course for ASCE that is offered nationally four times a year. He is frequently invited to make presentations to AASHTO technical committees during the group's annual meetings. In 2007, Sivakumar served as technical consultant to AASHTO Committee T18 on Bridge Management, Evaluation, and Rehabilitation.

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APPENDIX D

Finnish Statistical Process Controls in the Bridge Inspection Program

AS NOTED IN PAST SCANS, the Finnish Road Administration's (Finnra) Reference Bridge Program is noteworthy. Finnra uses 106 bridges and 26 steel culverts as a control sample or set of bridges from which it gathers baseline data using experienced in-house bridge inspection staff to fulfill a variety of needs. These needs include the following:

- Data on bridge serviceability and durability over time
- Trend analysis of data gathered on similar bridges and updating of deterioration models in the bridge management system
- Quality control of inspection data from nonreference bridges, using baseline data for comparison
- Identifying training and refresher training needs of inspectors
- Comparing inspector condition ratings against condition ratings provided by in-house staff. This evaluation is also used to provide quality points for selection of consultant inspectors.

Finnra monitors data quality control through the following:

- Bridge inspector qualifications
- Advanced yearly training day
- Quality measurements
- Reports from the bridge register
- Irregularity reports

Bridge Inspector Qualifications

Finnish bridge inspectors are certified upon completion of a two-phase training program. The first phase consists of a 4-day theoretical course on bridge measures, structural behavior, deterioration, maintenance repair and rehabilitation (MR&R), Finnra's bridge register (management system), conduct of the inspection, inspection methods, data, and quality control with a written examination. The second phase consists of 2 days: 1 day of training on the bridge site and a 1-day performance examination that includes a written test.

Inspectors must participate in yearly 1-day advanced training to renew their certification. Annual certification also serves as a calibration day for inspectors to ensure uniformity of assessments by all inspectors. The annual advanced yearly training day involves inspections of two bridges. The bridges used in the evaluation are rated beforehand by Finnra staff. The results provided after inspection to the candidate are compared to the baseline inspection. Finnra maintains records of each inspector's annual test inspection in a central database, and reviews and rates the results to determine personal quality points for each inspector. These personal quality points are used in the selection process for bridge inspection services. Repeated weak test results can lead to loss of certification.

Quality Measurements

In addition to the above, each region's bridge engineer is responsible for ensuring the skills of inspectors working in his or her region by making quality measurements. Every inspector involved in the inspections of the road region must participate in at least two control inspections during an inspection period.

Quality control inspections consist of general inspection of a structure. The actual number of quality control inspections conducted by an individual inspector varies, depending on the number of inspections he or she will perform during the period (table 4). The sample bridge must have at least 50 damage points (VPS).

Table 4. *Quality control inspections in 2005.*

Number of inspected bridges	Number of control inspections
1 … 100	2
101 … 300	3
> 300	4

The Finnra regional bridge engineer chooses a bridge with known inspection results. The inspectors to be evaluated, who must have no previous knowledge of the bridge, inspect the bridge in the presence of the Finnra engineer. The Finnra engineer reports the results of the inspections in the bridge register as personal quality results of the candidate inspectors. An irregularity report is created if any inspector's damage point deviation (PL), relative deviation (SP), or relative cost deviation (SPkust) in the quality measurement exceeds the maximum allowed values, as shown in figure 14.

Damage points (VP) are a function of the bridge structural part and the estimated condition of the structural part where the damage is located, the damage class, and the repair urgency class of the damage. The sum of damage points (VPS) describes the degree of bridge deterioration and the amount of damage, taking into account the length and the width of the bridge. The number is calculated from the sum of damage points assigned to nine main groups of structural elements.

Two quality parameters are measured: deviation (PL), calculated based on the damage points (VP), and relative deviation (SP), calculated based on the sum of damage points (VPS) or the sum of repair costs of the bridge.

Quality Reports Prepared for the Finnra Bridge Register

Finnra uses a variety of quality reports to support and assist quality control of the inspection program. Finnra has published quality reports yearly since 2002 in its internal report series. Review of the results of these reports on data quality during the past 3 years shows that the inspection data quality clearly improved after 2002, but it is partly better and partly worse than the 2003 data. Finnra believes that these reports have been invaluable in helping it identify needs for additional inspector training, revisions to inspection methods and procedures, and additional quality control activities (figure 15).

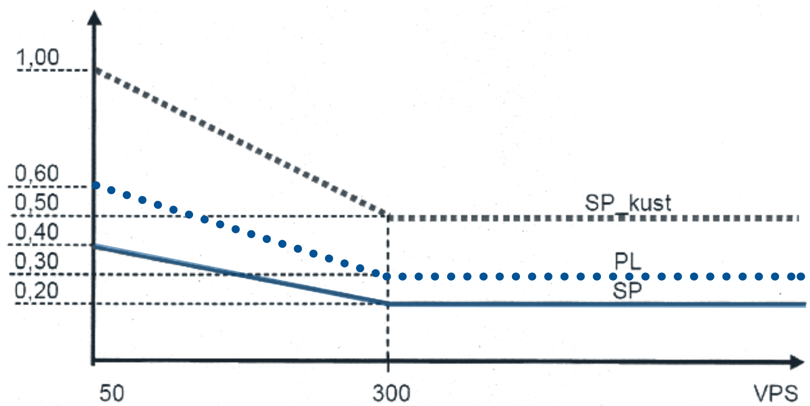

Figure 14. *Maximum allowed values for the deviation PL and relative deviations SP and SPkust.*

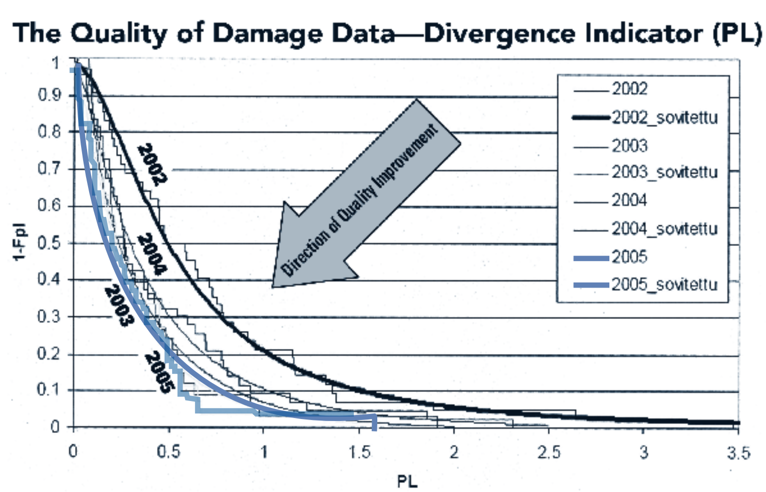

Figure 15. *Plot of divergence indicator from Finnra quality reports.*

Source: Finnish Road Administration

Calculation of Finnra Quality Parameters

1. Each bridge inspector determines damage points (VP) for the bridge.
2. The absolute values of the difference in each pair of inspectors' VP values are calculated.
3. The quotient of the maximum and minimum absolute values is calculated. If the quotient ≤ 3, the mean value of damage points will be the mean of VPs in all three inspections. If the quotient > 3, the mean value of damage points will be the mean of VPs of the two inspections with the minimum absolute value.
4. The inspector's results are then compared to the mean value. The assumption: the mean value is the right result. The deviation (PL) and the relative deviation (SP) are calculated as shown.

$$PL = \sum |VP_{i00} - Mean_{i00}| / \sum Mean_{i00}$$

$$SP = |VPS_i - \sum Mean_{i00}| / \sum Mean_{i00}$$

Structural part	Damage points by the inspectors VP$_1$	VP$_2$	VP$_3$	$\frac{\max \mid VP_i - VP_j \mid}{\min \mid VP_i - VP_j \mid}$	Mean
100	70	70	40	∞	70
200	50	40	30	2	40
300	150	200	0	4	175
400	10	20	0	2	10
500	0	0	0	1	0
600	50	30	20	3	33
700	0	0	0	1	0
800	51	30	20	3,1	25
900	0	0	0	1	0
VPS	**381**	**390**	**110**	**31,1**	**353**

Figure 16. *Example calculation of Finnra quality parameters.*

Calculation of the deviation (PL) for the inspector 1 gives

PL = (0+10+25+0+0+17+0+26+0) / 353 = 0,22 < 0,3

and the relative deviation (SP)

SP = | 381-353 | / 353 = 0,08 < 0,2.

As a result, no irregularity report is needed.

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