CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

4.1 CONCLUSIONS

This study has developed a design procedure for the application of extreme load events and the combination of their load effects in the *AASHTO LRFD Bridge Design Specifications* (1998). This is achieved by proposing a set of load factors calibrated using a reliability-based procedure that is consistent with the reliability methodology of the AASHTO LRFD specifications. The load events considered in this study include live loads, earthquakes, wind loads, ship collision loads, and scour. The reliability analysis of the effects of each load taken individually is performed using methods developed in previous bridge code calibration efforts (for the live loads and ship collisions) and during the development of other structural codes (for wind loads and earthquake loads). Because the current specifications for scour were not based on reliability methods, a scour reliability model has been developed for the purposes of this study. In addition, the Ferry-Borges model is used to evaluate the reliability of bridges under the combined effects of extreme load events. Results from the reliability of typical bridge configurations under the effects of individual threats are used to define target reliability levels for the development of load factors applicable for designing bridges that may be susceptible to a combination of threats. The objective is to recommend a rational and consistent set of load combination factors that can be implemented in future versions of the AASHTO LRFD specifications.

To achieve the objectives of the study, this project first reviewed the basic reliability methodology used during previous code calibration efforts. Basic bridge configurations designed to satisfy the current AASHTO specifications were analyzed to find the implicit reliability index values for different limit states for bridges subjected to live loads, wind loads, earthquakes, vessel collisions, or scour. The limit states considered include column bending, shearing failure, and axial failure of bridge columns, bearing failure of column foundations, and overtipping of single-column bents. The reliability analysis used appropriate statistical data on load occurrences and load intensities for the pertinent extreme events that were assembled from the literature and USGS websites. Statistical data on member and foundation capacities as well as load analysis models commonly used in reliability-based code calibration efforts were also used to find the probability of failure and the reliability index values for each extreme event. Reliability indexes were calculated for the same bridges when subjected to the combination of extreme events using the Ferry-Borges model. The results were subsequently used to calibrate load combination factors appropriate for implementation in the LRFD equations.

The load factors are proposed such that bridges subjected to a combination of events provide reliability levels similar to those of bridges with the same configurations but situated at sites where one threat is dominant. Thus, the proposed load factors are based on previous experiences with "safe bridge structures" and provide balanced levels of safety for each load combination. Because this study found that different threats produced different reliability levels, the target reliability indexes for the combination of events are selected in most cases to provide the same reliability level associated with the occurrence of the individual threat with the highest reliability index. Thus, when dealing with the combination of live load plus wind load or live load plus scour, the reliability index associated with live loads is used as target. When studying the reliability of bridges subjected to the combination of wind loads and scour, the reliability index associated with wind loads alone is chosen for target. Similarly, when studying the reliability of bridges under vessel collision with scour or vessel collision with wind load, the reliability index associated with vessel collisions is used for target. For combinations involving earthquake loads, it is the reliability index associated with earthquakes alone that is used for target. Combinations involving earthquakes are treated differently than other combinations because of the large additional capacity that would be required to increase the reliability levels of bridges subjected earthquake risks.

The analysis considered structural safety as well as foundation safety. For two-column bents, system safety is compared with member safety. The results show that the system produces an additional reliability index about 0.25 higher than the reliability index of the individual members, which is consistent with the results of Liu et al. (2001) for drilled shafts of two-column bents formed by unconfined concrete columns. Hence, the system factors calibrated by Liu et al. (2001) are applicable for the cases in which linear elastic analysis is performed to check bridge member safety. Liu et al. (2001) calibrated system factors for application on the left-hand side of the design equation to complement the member resistance factor. The cases for which the application of system factors is possible include the analysis of bridges subjected to combinations exclusively involving live loads, wind loads, and ship collision forces. The analysis for combinations involving earthquakes is based on the plastic behavior of bridge bents; thus, system safety is directly considered and no system factors need to be applied. Scour causes the complete loss of the load-carrying capacity of a column, and bridge bents subjected to scour erosion exposing the full foundation will have little redundancy. Thus, such failures should be associated with system factors on the order of 0.80 as recommended by Liu et al. (2001).

Results of the reliability analyses indicate that there are large discrepancies among the reliability levels implied in current design practices for the different extreme events under consideration. Specifically, the following observations are made:

- The AASHTO LRFD was calibrated to satisfy a target member reliability index equal to 3.5 for gravity loads. The calculations performed herein confirm that members provide reliability index values close to the target 3.5 for the different limit states considered. These limit states include column bending, axial failure and overtipping of one-column bents. Lower reliability index values are observed for foundation-bearing capacities for one-column and multicolumn bents.
- The system reliability index for the drilled shaft foundations of bridge bents subjected to earthquakes is found to be on the order of 2.9 for moment capacity or 2.4 for overtipping of single-column bents. Even lower reliability values are observed for bridge columns because of the higher response modification factor recommended for column design as compared with those recommended for foundation subsystems. Unlike the analysis for other hazards, the earthquake analysis procedure accounts for system capacity rather than for member capacity. This is because earthquake analysis procedures consider the plastic redistribution of loads, and failure is defined based on the ductility capacity of the members. Although relatively low compared with the member reliability index for gravity loads, the engineering community is generally satisfied with the safety levels associated with current earthquake design procedures as improvements in the reliability index would entail high economic costs.
- The reliability index for designing bridge piers set in small rivers for scour varies from about 0.47 to 1.66, which is much lower than the 3.5 target for gravity loads. In addition, failures caused by scour result in total collapse as compared with failures of members under gravity loads that cause local damage only. Local damage can be sustained by the system if sufficient levels of redundancy and ductility are present, which is not the case for foundations exposed because of scour. Hence, it is recommended to increase the reliability index for scour by applying a scour safety factor equal to 2.00. The application of the recommended 2.00 safety factor means that if current HEC-18 scour design procedures are followed, the final depth of the foundation should be 2.00 times the value calculated using the HEC-18 approach. Such a safety factor will increase the reliability index for scour from an average of about 1.0 to higher than 3.0. This increase will make the scour design methods more compatible with the methods for other threats.
- Although bridge design methods for wind loads provide an average member reliability index close to 3.0, there are large differences among the reliability indexes obtained for different U.S. sites. For this reason, it is recommended that research be undertaken to revise the existing wind maps so that they provide more consistent designs for different regions of the United States.
- The AASHTO vessel collision model produces a reliability index of about 3.15 for shearing failures and on the order of 2.80 for bending failures. The higher reliability index for shear is due to the higher implicit biases and conservative design methods. The presence of system redundancy caused by the reserve resistance provided by the bents, abutments, or both that are not impacted would increase the reliability index for bending failures to more than 3.00, making the safety levels more in line with those for shearing failures, which are brittle failures that do not benefit from the presence of redundancy.

The recommended load combination factors are summarized in Appendix A in a format that is implementable in the AASHTO LRFD specifications. The results illustrate the following points:

- The current load factors for the combination of wind plus live loads lead to lower reliability indexes than do those of either load taken separately. Hence, this study has recommended increasing the load factors for wind on structures and wind on live loads from the current 0.40 to 1.20 in combination with a live load factor of 1.00.
- The commonly used live load factor equal to 0.50 in combination with earthquake effects would lead to conservative results. This report has shown that a load factor of 0.25 on live load effects when they are combined with earthquake effects would still provide adequate safety levels for typical bridge configurations subjected to earthquake intensities similar to those experienced on the West and East Coasts. These calculations are based on conservative assumptions on the recurrence of live loads when earthquakes are actively vibrating the bridge system.
- For the combination of vessel collision forces and wind loads, a wind load factor equal to 0.30 is recommended in combination with a vessel collision factor of 1.0. The low wind load factor associated with vessel collisions compared with that recommended for the combination of wind loads plus live loads partially reflects the lower

rate of collisions in the 75-year design life of bridges as compared with the number of live load events.

- For the combination of vessel collisions and live load, it is recommended to reduce the live load factor from 0.50 to 0.25. This is proposed to bring this case more in line with the earthquake plus live load case. A higher wind load factor than live load factor is used in combinations involving vessel collisions to reflect the fact that the rate of vessel collisions increases during windstorms.
- A scour factor equal to 1.80 is recommended for use in combination with a live load factor equal to 1.75. The lower scour load factor for the combination of scour and live loads compared with the factor recommended for scour alone reflects the lower probability of having the maximum possible 75-year live load occur when the scour erosion is also at its maximum 75-year depth.
- A scour factor equal to 0.70 is recommended in combination with a wind load factor equal to 1.40. The lower scour factor observed for the combination with wind loads as compared with the combination with live loads reflects the lower number of wind storms expected in the 75-year design life of the structure.
- A scour factor equal to 0.60 is recommended in combination with vessel collision forces. The lower scour factor observed in combinations that involve collisions reflects the lower number of collisions expected in the 75-year bridge design life.
- A scour factor equal to 0.25 is recommended in combination with earthquakes. The lower scour factor with earthquakes reflects the fact that as long as a total wash out of the foundation does not occur, bridge columns subjected to scour exhibit lower flexibilities that will help reduce the inertial forces caused by earthquakes. This reduction in inertial forces partially offsets the scour-induced reduction in soil depth and the resulting soil resistance capacity.
- When scour is possible, the bridge foundation should always be checked to ensure that the foundation depth exceeds 2.0 times the scour depth obtained from the HEC-18 equations.
- For the cases involving a dynamic analysis such as the analysis for earthquakes, it is very critical that the case of zero scour depth be checked because in many cases, the presence of scour may reduce the applied inertial forces.
- When a linear elastic analysis of single-column and multicolumn bents is used, the system factors developed under NCHRP Project 12-47 should also be applied to complement the resistance factors (Liu et al., 2001).

4.2 FUTURE RESEARCH

The work performed as part of this study revealed that several issues related to the reliability analysis of bridge systems subjected to extreme load events need further investigation. These issues include the following areas discussed below.

4.2.1 Evaluation of Proposed Load Factors

This report has recommended several changes in the load factors for extreme events and their combinations. These recommendations are based on the reliability analysis of simplified models for typical bridge substructures subjected to individual extreme events and the combination of events. Extensive field evaluation and experimentation with the proposed recommendations using detailed structural analysis models should be undertaken. Some of these investigations may include extensive field measurements, data collection, and comparison of designs with evaluation of implied construction costs.

4.2.2 Determination of Appropriate Target Reliability Levels

The calibration of the load factors undertaken in this research follows a commonly used approach whereby the average reliability index from typical “safe” designs is used as the target reliability value for the new code. That is, a set of load factors and the nominal loads (or return periods for the design loads) are chosen for the new code such that bridges designed with these factors will provide reliability index values equal to the target value as closely as possible. This approach that has traditionally been used in the calibration of LRFD criteria (e.g., AISC and AASHTO) has led code writers to choose different target reliabilities for different types of structural elements or for different types of loading conditions. The choice of the different target βs raises the following question: If the reliability index (β) for live loads is 3.5 and for earthquake loads is 2.8, what should be the target when combining live loads and earthquake loads? In this report, it was decided that the higher reliability index should be used except for the cases involving earthquakes. The justification is that increasing the reliability index for earthquake threats would involve high construction costs, which society may not be willing to sustain. This subjective justification for using different target reliabilities can be formulated using a risk-benefit argument. For example, codes should tolerate a higher risk for the design of bridges (or structures) against a particular event if the costs associated with reducing this risk are prohibitive. Aktas, Moses, and Ghosn (2001) have presented examples illustrating an approach that can be used for determining the appropriate target reliability index values based on risk-benefit analysis. More work is needed in that direction to implement these concepts in actual bridge calibration efforts.

4.2.3 Reliability Models for Bridge Foundations

The analysis of bridge bents under the effect of the loads considered in this study is highly dependent on the accuracy of the foundation analysis models and the uncertainties associated with predicting the strength capacity of bridge foundations. Similarly, the effects of the soil-structure interaction on the response of bridge bents subjected to impact loading (i.e., vessel collisions) or cyclic dynamic loads (e.g., earthquakes and winds) need to be carefully considered. Currently, there is little information available to describe the uncertainty inherent in commonly used foundation analysis procedures. These uncertainties are caused by modeling assumptions, spatial variations of soil properties, and statistical uncertainties due to the limitations in the soil samples that are normally collected as part of the foundation design process. Some preliminary research work is currently ongoing under NCHRP Project 12-55. However, NCHRP Project 12-55 will not address all the aspects of the problem—particularly the dynamic effects of the loads on soil strength—and more research work is needed on this highly important subject. Reliability models should provide consistency between foundation analysis procedures and structural analysis models to better evaluate the reliability of complete structural systems and the interaction among bridge superstructures, substructures, and foundations.

4.2.4 Live Load Models

The statistical database used during the development of the live load model for the AASHTO LRFD code was collected from truck weight surveys in Ontario, Canada, and was supplemented by limited samples from Michigan. Some of the limitations in the data include the following:

1. The Ontario truck weight data were collected in 1975 in a Canadian province that had higher truck weight limits than the ones currently in effect in the United States.
2. The Ontario data were biased toward heavy trucks (i.e., only trucks that were believed to be heavily loaded were weighed); this would obviously produce a weight histogram showing an unusually high percentage of overloaded vehicles.
3. The Michigan truck weight data were also biased because Michigan allows higher truck weight limits for certain truck configurations than do most other U.S. states.
4. The statistics on multiple-truck occurrences used in the calibration were not based on specific observations and were unusually high compared with those observed on typical highways.
5. The average daily truck traffic used in the calibration was low compared with that observed on typical highways.
6. The same live load factor and live load model were proposed for all bridges, although it is widely accepted that bridges in rural areas with lower traffic counts are less likely to reach the projected maximum live load than are bridges in heavily traveled industrial regions.

In general, these assumptions had to be made during the original calibration because of lack of sufficient data. It is herein emphasized that, despite the limitations in the statistical database, the calibration process produces conservative estimates of the reliability levels and robust sets of load factors. However, the stated limitations in the database demonstrate the necessity of collecting more data in order to obtain a better assessment of the risks involved in current designs for various types of bridges and also to provide a mechanism to include site-specific information. The load combination factors depend on the number of live load events expected during the occurrence of the other loads. Hence, more information needs to be gathered on the rate and intensities of live load events. Future live load models should be sufficiently flexible to account for variations in these factors depending on the sites considered, including the legal truck weight limits in effect at the site and the intensity of the traffic.

4.2.5 Wind Load Models

Considerable concern has been expressed regarding the consistency of the data presented in the ASCE 7 maps that are the basis for the AASHTO maps for wind speed intensities. Some of the most pressing issues raised by researchers include the following:

1. Determining the proper probability distribution type that most adequately represents the intensity of wind speeds for hurricanes and for regular storms;
2. Considering statistical uncertainty and the effect of the tails of the probability distributions;
3. Examining the relationship between the actually measured wind speeds, including the regional variations of wind intensities, and the adequacy of the wind speed envelopes provided in the published maps;
4. Addressing the inconsistencies between the recurrence intervals used in the maps for hurricane winds and windstorms;
5. Remedying the lack of adequate models for representing special cases such as tornados; and
6. Developing models to account for wind gusts on bridges.

It is clear that the effect of winds on civil engineering structures in general and on bridge structures in particular did not receive the same attention given to other loads, and more work is needed in this field in order to develop rational and consistent design methods.

4.2.6 Scour Models

It is widely accepted that “a majority of bridges that have failed in the United States and elsewhere have failed due to scour” (AASHTO, 1994). This is confirmed by Shirole and Holt (1991), who observed that over a 30-year period, more than 1,000 of the 600,000 U.S. bridges have failed and that 60% of these failures are because of scour while earthquakes accounted for only 2%. Of course, there are many more bridges that are posted or otherwise taken out of service due to their inadequate strengths (because of deterioration, low rating, fatigue damage, etc.). Nevertheless, scour is considered to be a critical cause of failure because its occurrence often leads to total collapse. For these reasons, developing methods for the design and maintenance of bridge foundations for scour is currently considered to be a top priority for agencies concerned with the safety of bridges, and there is considerable research effort devoted to scour. The currently accepted model for scour design and evaluation is the HEC-18 model. HEC-18 stipulates that the scour depth produced by a given flood is not affected by previous (or existing) scour at the site. Hence, the maximum scour in a given return period is a function of the maximum flood observed in that period and is not affected by previous smaller floods that may have occurred within that same period. In addition, the HEC-18 model assumes that the flood duration is always long enough for the full scour depth corresponding to the flood velocity to be reached. Although, for live bed conditions, the scour hole is normally assumed to refill as the scour-causing flood recedes, the available literature does not provide precise information on how long it normally takes for the foundation to regain its original strength. This is believed to depend on the type of material being deposited by live-bed streams. It is also noted that HEC-18 was developed based on small-scale experiments involving sandy materials. Scale effects and the effects of different soil types need to be addressed in future research work. The importance of the scaling effect is reflected by the large differences observed in the reliability levels of rivers based on their discharge rates and expected scour depths. The differences between river scour and tidal scour should also be addressed. Simultaneously statistical data need to be gathered on each of the parameters that affect scour in order to develop a comprehensive reliability model for scour that is compatible with the models available for the other extreme events.

4.2.7 Vessel Collision Models

AASHTO's *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* developed a detailed, reliability-based model for studying the safety of bridges subjected to vessel collision forces (AASHTO, 1991). The model accounts for the major parameters that affect the rate of collisions and the magnitude of the collision forces. However, more data are needed to verify several of the assumptions used in the AASHTO model, including the effect of vessel size on the geometric probability of collision, and to correlate the rate of accidents with site-specific information on the type and size of the vessels, channel size and geometry, and other conditions. It is especially important to find explanations for the differences observed between the collision forces generated in laboratory experiments or computer analyses and actual damage observed after collisions in the field. These differences were lumped into a modeling random variable that was identified by the AASHTO guide specifications as the random variable $x = P_{\text{actual}}/P_{\text{calculated}}$. Efforts should be made to reduce the discrepancies between the predicted and observed forces to reasonable levels.

4.2.8 Earthquakes

Considerable effort has been expended over the last 3 decades on developing rational and consistent models for studying the safety of bridges subjected to earthquakes. To provide reasonable confidence levels, hazard maps and uniform hazard response spectra have been developed for a fine grid covering the whole United States. The issues that still require more research include the following:

1. Modeling of the ductility capacity and the relationship between ductility capacity and response modification factors, particularly for multidegree-of-freedom systems, taking into consideration the effects of the response modification factors on the overall reliability of bridge systems;
2. Development of SSI models that would provide consistent results for deep and shallow foundations;
3. Consideration of soil nonlinearity while determining the natural periods of the system;
4. Classification of soils for site amplification parameters and the consideration of uncertainties in determining the site factors.

4.2.9 Consideration of Modeling and Statistical Uncertainties

The research described in this report accounts for statistical and modeling uncertainties by representing these through random variables that are directly included in the calculations of the reliability index, β. For example, during the calibration of the load factors, different COV values are used to reflect the level of confidence associated with estimating the earthquake intensities at different sites. Similarly, different COV levels are used to reflect the number of data points used to estimate the mean and standard deviations of wind speeds at different sites throughout the United States. However, the final load factors proposed are averaged from all the sites and, thus, do not reflect the differences in the modeling and statistical uncertainties in a direct manner. Work on including uncertainty analysis in structural reliability formulation has been ongoing for a number of years (e.g., see the work of Ditlevsen [1982, 1988] and Der Kiureghian [2001]). However, there has not been a formal procedure that would explicitly account for the modeling and statistical uncertainties during the calibration of load factors and the development of structural design codes.

One possible approach would consist of calibrating two load factors for each load. One load factor would be a "generic load factor" that would be applicable for all sites and that would reflect the inherent randomness of the physical parameters describing the effects of the load under consideration. The second load factor would reflect the confidence level associated with the statistical data available to estimate the intensity of the loads at the particular site. The second load factor would also describe the difference between the results from the structural analysis and those observed in the field. Such an approach would encourage design engineers to collect more data on the loads and on the load intensities expected at the designated (or existing) bridge site and would also encourage the engineers to utilize more advanced analysis procedures or field measurements to reduce the modeling uncertainties associated with using simplified analysis and design methods. Moses (2001) has generally followed a similar approach during the calibration of the load and resistance factor rating and load capacity evaluation procedures for existing bridges. The possibility of employing the same format using a more formal analysis of uncertainty should be investigated.