NCHRP

REPORT 489

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Design of Highway Bridges for Extreme Events

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 489

Design of Highway Bridges for Extreme Events

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SUBJECT AREAS
Bridges, Other Structures, and Hydraulics and Hydrology

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By David B. Beal
Staff Officer
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NCHRP Report 489: Design of Highway Bridges for Extreme Events contains the findings of a study to develop a design procedure for application of extreme event loads and extreme event loading combinations to highway bridges. The report describes the research effort leading to the recommended procedure and discusses the application of reliability analysis to bridge design. The material in this report will be of immediate interest to bridge engineers and bridge-design specification writers.

The magnitude and consequences of extreme events such as vessel collisions, scour caused by flooding, winds, and earthquakes often govern the design of highway bridges. If these events are considered to occur simultaneously, the resulting loading condition may dominate the design. This superpositioning of extreme load values frequently increases construction costs unnecessarily because a simultaneous occurrence of two or more extreme events is unlikely. The reduced probability of simultaneous occurrence for each load combination may be determined using statistical procedures.

The *AASHTO LRFD Bridge Design Specifications* developed under NCHRP Project 12-33 cover the basic design combinations with dead load and live load. Extreme load combinations were not considered in the load resistance factor design (LRFD) calibration because of the lack of readily available data concerning the correlation of extreme events. Nevertheless, a probability-based approach to bridge design for extreme events can be accomplished through incorporation of state-of-the-art reliability methodologies.

The objective of NCHRP Project 12-48 was to develop a design procedure for the application of extreme event loads and extreme event loading combinations to highway bridges. This objective has been achieved with a recommended design procedure consistent with the uniform reliability methodologies and philosophy included in the *AASHTO LRFD Bridge Design Specifications*. Four new extreme event load combinations are included to maintain a consistent level of safety against failure caused by scour combined with live load, wind load, vessel collision, and earthquake, respectively.

This research was performed at the City College of the City University of New York, with the assistance of Dr. Fred Moses. The report fully documents the methodology used to develop the extreme load combinations and the associated load factors. Recommended specification language is included in a published appendix. All appendixes to the report are included on *CRP-CD-30*.

CONTENTS

DESIGN OF HIGHWAY BRIDGES FOR EXTREME EVENTS

SUMMARY

The current AASHTO load resistance factor design (LRFD) specifications were developed using a reliability-based calibration that covered gravity loads consisting of the basic combination of permanent (or dead) load plus live load. The other load combinations were obtained from previous generations of specifications and from the experience of bridge engineers and, thus, may not be consistent with the reliability methodology of the LRFD specifications. The objective of this study is to develop a design procedure for the consideration of extreme events and the combination of their load effects in the *AASHTO LRFD Bridge Design Specifications.* Extreme events are defined as man-made or environmental hazards having a high potential for producing structural damage but are associated with a relatively low rate of occurrence. The extreme events considered in this study include live loads, earthquakes, wind loads, ship collision forces, and scour.

According to the AASHTO LRFD, bridges should be designed for a 75-year return period. The probability that a bridge will be subjected in its 75-year design life to an extreme event of a certain magnitude depends on the rate of occurrence of the event and the probability distribution of the event's intensity. Generally speaking, there is low probability that several extreme events will occur simultaneously at any point in time within a bridge's design life. Even when simultaneous occurrences do occur, the chances that all the events are at their highest intensities are very small. To account for these low probabilities, engineers have historically used the one-third stress-reduction rule when combining extreme environmental events, such as wind or earthquake loads, with gravity loads. This rule, which dates back to the early years of the 20th century, has been discredited; it is generally accepted that a more appropriate procedure should use load combination factors derived from the theory of structural reliability.

The aim of structural reliability theory is to account for the uncertainties encountered during the safety evaluation of structural systems or during the calibration of load and resistance factors for structural design codes. The uncertainties considered include those associated with predicting the load-carrying capacity of a structure, the intensities of the extreme events expected to be applied during the structure's design life, the frequency of these loading events, and the prediction of the effects of these events on the structure.

To ensure the safety of highway bridges under the combined effects of extreme events, this study develops load factors appropriate for inclusion in the AASHTO LRFD design-check equations. The reliability analysis of the effects of each threat 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 AASHTO specifications for scour are not based on reliability methods, a scour reliability model is developed for the purposes of this study. Results of reliability analysis of typical bridge configurations under the effect 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 combinations of threats.

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

The Ferry-Borges model assumes that each extreme event type produces a sequence of independent load effects, each lasting for an equal duration of time. The service life of the structure is then divided into equal intervals of time. The probability that a load occurs in an arbitrary time interval can be calculated from the event's occurrence rate. Simultaneously, the probability distribution of the intensity of the load given that the event has occurred can be calculated from statistical information on load intensities. The probability that a second event would occur in the same time interval when the first load event is on can also be calculated from the rate of occurrence of the second load and the time durations of each load. After calculating the probability density for the second load given that it has occurred, the probability of the intensity of the combined load effects can be calculated using a convolution integral. The load combination problem consists of predicting the maximum value of the combined load effects that is likely to occur in the lifetime of the bridge. Although the Ferry-Borges model gives a simplified representation of the actual loading phenomenon, this model is more accurate than other load combination rules such as Turkstra's rule because it takes into consideration the rate of occurrence of the loads and their time durations. The probability distribution of the maximum value of the combined load effect is used along with statistical data on bridge member and system resistances to find the probability of failure and the reliability index, β.

The load factors proposed in this study are calibrated such that bridges subjected to a combination of events provide reliability levels similar to those of bridges with the same configurations but situated in 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. The results of this study indicate that different threats produce different reliability levels; therefore, 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 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 even if the reliability for earthquakes alone produces a lower reliability index. Combinations involving earthquakes are treated differently than other combinations because of the large additional capacity and resulting construction costs that would be required to increase the reliability levels of bridges subjected to earthquake risks.

The analysis considers structural safety as well as foundation safety. For multicolumn bents, system safety is compared with member safety. The results show that the system produces a reliability index about 0.25 higher than the reliability index of the individual members for two-column bents formed by unconfined concrete columns. Hence, the system factors calibrated under NCHRP Project 12-47 are applicable for the cases in which linear elastic analysis is performed to check bridge member safety (see *NCHRP Report 458: Redundancy in Highway Bridge Substructures* [Liu et al., 2001]). NCHRP Project 12-47 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 depths exceeding the foundation depth will have little redundancy. Thus, such failures should be associated with system factors on the order of 0.80 as recommended by NCHRP Project 12-47.

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 in this study confirm that bridge column bents provide reliability index values close to the target 3.5 for the different limit states considered. These limit states include column bending and axial failure for one-column and multicolumn bents, as well as overtipping of one-column bents. Bearing failure of the soil may produce lower reliability levels depending on the foundation analysis model used.
- The system reliability index for 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 founded on pile extensions (drilled shafts) that can be inspected. Lower reliability index values are observed for other subsystems depending on the response modification factors used during the design of their components. Unlike the analysis for other hazards, the earthquake analysis procedure accounts for system capacity rather than for member capacity because the earthquake analysis process accounts for plastic redistribution of loads and failure is defined as a function of the ductility capacity of the members. Although this is 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, and increases in the currently observed safety levels would entail high economic costs. For this reason, the target reliability index for load combination cases involving earthquakes is chosen to be the same reliability index calculated for designs satisfying the current design criteria when earthquakes alone are applied. On the other hand, a future review of the response modification factors used in earthquake design is recommended in order to produce more uniform reliability levels for all system types.

- The reliability index for designing bridge piers for scour in small rivers varies from about 0.45 to 1.8, depending on the size of the river and the depth and speed of the discharge flow. These values are much lower than the 3.5 target for gravity loads and are also lower than the index values observed for earthquakes. In addition, failures caused by scour may often lead to total collapse as compared with failures of members under gravity loads. Therefore, it is recommended to increase the reliability index for scour by applying a scour safety factor equal to 2.0. The application of the recommended 2.0 safety factor means that if current HEC-18 scour design procedures are followed, the final depth of the foundation should be 2.0 times the value calculated using the HEC-18 equation. Such a safety factor will increase the reliability index for scour from an average of about 1.0 for small rivers to a value slightly higher than 3.0, which will make the scour design safety levels compatible with the safety levels for other threats. However, a review of the HEC-18 equations is recommended in order to provide more uniform safety levels for all river categories.
- While 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 future research in wind engineering develop new wind design maps that would provide more uniform safety levels 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 presence of system redundancy caused by the additional bending moment resistance 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.

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 1.0 (instead of the current live load factor of 1.35).
- 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 observed on either the west or 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.
- 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 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 in 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 combination with collision forces 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 washout 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-resisting capacity.

With regard to the extreme loads of interest to this study, the recommended revisions to the *AASHTO LRFD Bridge Design Specifications* (1998) would address the loads by ensuring that the factored member resistances are greater than the maximum load effects obtained from the following combinations (see following paragraphs for variable definition):

- Strength I Limit State: $1.25\,DC + 1.75\,LL$
- Strength III Limit State: $1.25\,DC + 1.40\,WS$
- Strength V Limit State: $1.25\,DC + 1.00\,LL + 1.20\,WS + 1.20\,WL$
- Extreme Event I: $1.25\,DC + 0.25\,LL + 1.00\,EQ$
- Extreme Event II: $1.25\,DC + 0.25\,LL + 1.00\,CV$, or
  $1.25\,DC + 0.30\,WS + 1.00\,CV$
- Extreme Event III: $1.25\,DC$; $2.00\,SC$, or
  $1.25\,DC + 1.75\,LL$; $1.80\,SC$
- Extreme Event IV: $1.25\,DC + 1.40\,WS$; $0.70\,SC$
- Extreme Event V: $1.25\,DC + 1.00\,CV$; $0.60\,SC$
- Extreme Event VI: $1.25\,DC + 1.00\,EQ$; $0.25\,SC$

The presence of scour is represented by the variable *SC*. The semicolon indicates that the analysis for load effects should assume that a maximum scour depth equal to $\gamma_{SC}\,SC$ exists when the other load events are applied where *SC* is the scour depth calculated from the HEC-18 equations. When scour is possible, the bridge foundation should always be checked to ensure that the foundation depth exceeds 2.00 *SC*. For the cases involving a dynamic analysis such as the analysis for earthquakes, it is critical that the case of zero scour depth be checked because in many cases, the presence of scour may reduce the applied inertial forces. The resistance factors depend on the limit states being considered. When a linear elastic analysis of single and multicolumn

bents is used, the system factors developed under NCHRP Project 12-47 should also be applied.

In the equations given above, *DC* represents the dead load effect, *LL* is the live load effect, *WS* is the wind load effect on the structure, *WL* is the wind load acting on the live load, *EQ* is the earthquake forces, *CV* is the vessel collision load, and *SC* represents the design scour depth. The dead load factor of 1.25 would be changed to 0.9 if the dead load counteracts the effects of the other loads.

The recommended changes in the AASHTO LRFD consist of adding Extreme Event Cases III through VI, which consider scour. In addition, Extreme Event II is modified to include a check of either live loads or wind loads with vessel collision forces. A higher wind load factor than live load factor is used to reflect the fact that the rate of vessel collisions increases during the occurrence of windstorms.