LRFD BRIDGE DESIGN – THE NEXT STEP IN DESIGN PHILOSOPHY

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ABSTRACT

The reason for design philosophy movements toward LRFD design procedures, including the AASHTO LRFD Bridge Design specifications, is to account for variability in the loading and strength parameters that affect the behavior of the member. This design philosophy also results in more consistent reliabilities in designs across the entire spectrum covered by the specifications. This methodology also allows a means to incorporate changes as more information on variability in parameters is obtained and to account for new designs utilizing innovative materials and/or procedures. The methodology, however, is established for the design of individual members at various separate limit states. The next logical step in the progress of design philosophy is to design the bridge as a system rather than a compilation of individual members. This will require assessing the system reliabilities of current designs on a complete bridge system basis. Once this is determined, a target reliability, similar to the current target reliability index, β, of 3.5 used for individual members design, can be established. The general design methodologies of the past, present, and this future overall system process are discussed.

Keywords: LRFD Bridge Design, System Reliability, Reliability Index, Bridge Analysis, and Limit States.

INTRODUCTION

Design philosophies change over time as experience and knowledge is gained. In the field of structural engineering, the majority of design requirements have been codified to ensure a level of safety for the public. The design requirements within specifications and codes have often been simplified to allow the practitioner ease of use and to speed the process of analysis and design while still assuring functioning and safe designs. Vast improvements in technology have allowed an increase in the efficiency of designers. In addition, designers now have the ability to deal with more complex systems and to incorporate more complex design criteria. There is often a resistance to change in design philosophies based on the often stated opinion that if the design procedures worked before why should there be a change. However, in order to advance the field and improve designs to deal with ever increasing demands, changes are necessary.

PREVIOUS DESIGN PHILOSOPHY

The previous design philosophy typically incorporated a level of safety through the use of a safety factor. This was the basis for Allowable Stress Design (ASD). The advantage of ASD was that a single factor was used. However, since the factor of safety was to account for uncertainties in all the parameters of the design, this process was limited because the method did not account for the wide range of variability of the parameters. In addition, the single factor of safety did not account for designs that incorporated new design processes, different construction techniques, different materials, and/or different loading. In bridge design, Load Factor Design (LFD) followed ASD. The LFD procedure did incorporate load and resistance factors, but the factors were developed to match the designs developed via ASD. Variability of the loading and resistance of the members was not incorporated into the factors. The resulting designs by ASD (and hence LFD) resulted in designs with reliabilities that varied based on the span of the member, ratio of the dead to live load, and various other parameters.

CURRENT DESIGN PHILOSOPHY

The current design procedure being used in many structural design codes and standards, including bridge design is the Load and Resistance Factor Design (LRFD) procedure. This procedure accounts for the variability in the load and resistance parameters. In addition, the reliability of designs resulting from the LRFD methodology is more consistent regardless of the span or type of bridge. The LRFD procedure also has the advantage of being easier to update when more information becomes available with regard to the variability of parameters, whether this variability changes due to better sampling techniques or improved manufacturing and construction procedures. In addition, incorporating new materials and or design techniques within the methodology is straightforward.

Though the LRFD methodology is advantageous over previous methods, it is still being applied to element design and not overall system design.

FUTURE DESIGN PHILOSOPHY

Undoubtedly, exceeding an ultimate strength limit state of a member is more severe than exceeding a serviceability limit state. However, exceeding a limit state for total failure of the entire structure is more severe than failure of an individual member, as depicted in Figures 1 and 2. Though codes and specifications account for some failure modes of an entire structure such as complete structure stability, the major focus is on individual member failure. As the ability of engineers to analyze and design becomes more efficient through computing techniques and the understanding of structural behavior, the next logical step in the development of design procedures is to incorporate the entire structure rather than individual members. This will provide more optimum designs by making components that are more critical to the entire system more reliable and those not as critical more efficient.

Fig. 1 Failure of a Bridge Component

Fig. 2 Failure of a Complete Bridge

Research has been performed on the reliability of some bridge systems[1,2]. The research has shown a wide range of reliability for varying spans, girder spacing, and the bridge type. This is not surprising since the AASHTO LRFD Bridge Specification[3] was calibrated to result in consistent reliabilities based on individual member reliabilities and not entire system reliability. Research has also been performed to incorporate the reliability of the bridge system through redundancy of the bridge system into specifications[4]. Here redundancy was defined as the system reliability compared to individual member reliability. The change in a system's reliability over time has also been investigated[5]. Though work has been done in these areas, it has not been incorporated into design procedures on a regular basis. This is due to the lack of significant data to make the process sufficient to incorporate system reliability into procedures.

CURRENT SYSTEM RELIABILITY

The first step in the process to develop procedures based on system reliability should follow those of previous code and specification developments. This process would evaluate current designs to determine the level of structural system reliability inherent in designs based on individual member reliability based designs. Though some of this has been done, more must be completed. In order to perform system reliability analyses on current designs, the type of structural system has to be determined. The type of structural systems for reliability analyses can be separated into the broad categories which include series systems, parallel systems and hybrid systems that are combinations of series and parallel systems. Series systems can be thought of as the "weakest link" type of system where failure of a single member leads to complete structural failure. Common examples of series systems would include determinate trusses and slab bridges. Parallel systems typically are systems where multiple members would need to fail before the entire system would fail. Examples of parallel systems would include frame systems and multiple girder slab bridges. In general, series systems increase the probability of failure compared to individual member reliability. The opposite is true for parallel systems. This assumes the members are not correlated. Increasing correlation between members results in the reliability of the system being closer to the reliability of the individual members[6].

Therefore, numerous reliability analyses of bridge systems will be necessary to develop an overall view of existing designs. This in itself can be a significant undertaking. Analyses will have to be capable of determining system failure. The limit state for the failure would also have to be defined such as yielding (ductile properties) or reaching ultimate strength (brittle properties). Other limit states may also be considered such as reaching a global system deflection or a reduced capacity if a member has failed. Determining the reliability for a purely series system would not be overly difficult once these limit states are defined since a series system would fail once a single member fails. However, the majority of systems are parallel or hybrid systems. Analyzing parallel and hybrid systems can be a difficult task due to load transfer behavior once a member has failed. The load transfer would be affected by the properties of the member (ductile or brittle), support conditions, member location within the system, load placement, and other components such as the deck, bracing, and diaphragms.

The classification of the system can be complex and debatable. For example, the superstructure of a multi-girder slab bridge would be considered a parallel system. However, when considering the substructure within this same system where a failure of an abutment or pier could lead to failure of the entire system, the entire system might be considered a hybrid system. Even if the superstructure is considered, other components such as the deck and diaphragms could also be incorporated into the model making it a hybrid system.

Consider a general example of a two-span multi girder overpass bridge. The probability of failure of the system could be thought of as shown in Equation 1.

$$P_{f(sys)} = P_{f(super)} \cup P_{f(sub)} \tag{1}$$

where:

$P_{f\ (sys)}$ = the probability of failure of the bridge system
$P_{f\ (super)}$ = the probability of failure of the bridge's superstructure
$P_{f\ (sub)}$ = the probability of failure of the bridge's substructure
$\cup$ = mathematical operator for the union of two events

The probability of failure for the superstructure could consider the probability of failure of the girders and the deck as shown in Eq. 2.

$$P_{f(super)} = P_{f(girders)} \cup P_{f(deck)} \tag{2}$$

The failure of the girders and the deck could be taken as parallel systems where the probability of failure can be found by Eq. 3.

$$P_f = \prod_{i=1}^{n} P_{f(i)} \tag{3}$$

where:

$\prod$ is the product mathematical operator

For the girders this is easily understandable because there are a discreet number of girders in the bridge. However, the deck may be left to interpretation because of its continuous nature in the longitudinal and transverse directions. The resulting question is how much of the deck must fail before it is considered failed? One possible method is to consider a transverse strip of the deck. The parallel system would then consist of the deck members between the girders and the overhangs.

The failure of the substructure could be thought of as shown in Eq. 4.

$$P_{f(sub)} = P_{f(pier)} \cup P_{f(abut.1)} \cup P_{f(abut.2)} \tag{4}$$

where:

$P_{f\ (pier)}$ = the probability of failure of the pier
$P_{f\ (abut.\ 1)}$ = the probability of failure of the bridge's first abutment
$P_{f\ (abut.\ 2)}$ = the probability of failure of the bridge's second abutment

The probability of failure for the pier would be dependent on the type of pier. If a multi column pier exists, this also could be taken as a parallel subsystem since more than one column would likely have to fail before the pier failed. The probability of failure for the abutments would also be dependent on the type of abutment, but would likely be considered a single component with failure coming from erosion or soil stability. Table 1 shows results assuming values for the probability of failure for a girder, part of the deck, the columns of the pier, and the abutment. This simplified analysis assumes that the failure events are mutually exclusive and that failure of the superstructure would result when two girders fail or the deck strip fails from the formation of two plastic hinges. The failure of the substructure occurs when either of the abutments or pier fails. The pier failure is defined when two columns fail. In addition, the probability of failure for each member type is taken as the same value, i.e. girder 1 and girder 2 have the same probability of failures.

Table 1: Bridge Components and System Failure Probabilities

Component	Probability of Failure			
	Case 1	Case 2	Case 3	Case 4
Girder	2.5×10^{-4}	2.5×10^{-5}	1.25×10^{-4}	1.25×10^{-4}
Deck	2.5×10^{-4}	2.5×10^{-4}	1.25×10^{-4}	1.25×10^{-4}
Column	2.5×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	1.25×10^{-4}
Abutment	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
Superstructure	1.25×10^{-7}	6.31×10^{-8}	3.13×10^{-8}	3.13×10^{-8}
Substructure	6.45×10^{-8}	6.45×10^{-8}	6.45×10^{-8}	1.76×10^{-8}
System	**1.90×10^{-7}**	**1.28×10^{-7}**	**9.58×10^{-8}**	**4.89×10^{-8}**

As shown in Table 1, decreasing the probability of failure for the girders is not as effective as decreasing the probability of failure of the deck and girders to a lesser degree (Case 2 compared to Case 3) for this particular example. A decrease in the probability of failure for the columns leads to a further decease in the system probability. Therefore, for this particular simple example, it would be more beneficial to slightly increase the reliability of several components of the system compared to significantly increasing a single component's reliability from an overall bridge system standpoint.

DATA

Though significant data has been obtained for the analysis of the reliability of individual members, additional data will be required for system reliability. Data will be required on the correlation between the variables considered in the analyses. For example, prestressed concrete members produced at the same facility would likely be positively correlated. The facility may produce a higher strength concrete than specified in the design leading to a higher flexural strength. Conditional probabilities may also need to be considered though a structural analysis may help with this aspect. An example of a conditional probability is given that member x has failed, the probability that member y fails will be different than if member x had not already failed. As the statistical database for variables and correlation between the variables grows, it can be incorporated into the design philosophy.

TARGET SYSTEM RELIABILITY

Reliability is often measured in terms of a reliability index, β. Once current designs have been evaluated based on a system reliability, a target reliability index, β_{sys}, will have to be established. Undoubtedly, β_{sys} will be dependent on the existing levels of reliability that are inherent in specifications developed on individual member reliabilities since past knowledge of safe designs should be considered. In addition, β_{sys} will be larger than current member reliabilities. This is expected due to the severe consequences as a result of a system failure compared to a single member failure, and the fact that the majority of systems will be parallel or hybrid systems. The current AASHTO LRFD Bridge Design Specification was developed using a target reliability index of 3.5. Reliability indices for bridge systems are in the range of 6 to 12[1,2]. Though the target reliability index for individual members is generally fixed, β_{sys} may consist of several distinct values. This may be necessary to incorporate the importance of strategic bridges and those that may not be as critical.

CALIBRATION

With a target reliability index or indices determined, calibration of the specification can occur to develop consistent designs from the system reliability viewpoint. This could lead to different reliability designs of components depending on the parameters of bridge system they are incorporated into since they will affect the overall system reliability.

CONCLUSIONS

AASHTO's current LRFD Bridge Design Specification was developed utilizing reliability theory to account for the variability of many of the parameters involved in the evaluation of members and components within bridges. The next step in the design philosophy is to incorporate the overall bridge system reliability into the specification since an overall system failure is more critical than an individual member failure. Limited work has been performed in bridge system reliability, but the work so far has shown that bridge system reliabilities based on individual member designs are not consistent. Therefore, the area of study of bridge system reliability is even more necessary to produce consistent designs. This research will not only need to include the system reliability analyses of a wide variety of bridges, but also the associated research that will support this effort such as data determination of correlation between components.

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