Effects of Damage and Redundancy on the Safety of Existing Bridges

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Many existing bridges are damaged. The older these bridges are, the higher their probability of being damaged. Yet, they continue to function and exhibit higher capacities than those associated with their designed vehicular loads. This may be the result of several factors, but the prevalent explanation among researchers today is that the existing bridges have a much greater amount of reserve strength than that anticipated by the original bridge designer. This indicates a need for determining an effective means for modeling and evaluating existing bridges, particularly for those exceeding their design life. The present study primarily reviews definitions of deterministic and probabilistic system redundancy measures which could be used in the design and evaluation of highway bridges. Some of these measures are used to evaluate the redundancy of an existing steel girder bridge. In this context, corrosion and accidental damages are simulated and the bridge redundancy is evaluated by using three-dimensional nonlinear finite element and probabilistic system analyses. The bridge damage - redundancy - reliability interaction is also studied.

INTRODUCTION

Despite the fact that the need for redundancy ability in highway bridges has already been recognized by AASHTO*(1)*, no criteria pertaining to quantify redundancy are explicitly specified within current bridge design codes. With heavier loads on existing bridges and increasing allowable stresses in newly designed structures, logical procedures would be required to determine the load carrying capacity and the redundancy level in bridge structures.

The need for redundancy in highway bridges can also be seen from a survey by the ASCE-AASHTO Committee on Redundancy of Flexural Systems*(2)* conducted on damaged bridges, which indicated that few bridge structures have collapsed when redundancy was present. Many of the reported collapses involved truss bridges with essentially no redundancy.

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Additionally, with the expanding usage of reliability theory in structural engineering, probabilistic procedures for bridge design and evaluation are gaining wide acceptance in the structural engineering community*(3,4)*. In the past, most structural analysis studies were directed toward single component deterministic analysis. Today, the need to introduce system redundancy and reliability measures in structural analysis and design is obvious*(5)*. However, while there has been much research into the safety of structures and the development of probabilistic design codes*(6-9)*, little work has yet been done on quantifying the level of redundancy and its impact on bridge reliability*(10-13)*.

In view of the above, the need for a method which quantifies structural redundancy levels in the design and evaluation of highway bridge systems is evident. This paper primarily reviews definitions of deterministic and probabilistic bridge redundancy measures. It also reports analytical investigations into the redundancy evaluation of an existing steel girder bridge using three-dimensional nonlinear finite element analysis and damage scenarios. In this context, corrosion and accidental damages are simulated. The redundancy measures used in evaluating the existing bridge offer useful information to quantify the effects of various damage states on bridge reliability and the availability of warning before total bridge collapse occurs.

BRIDGE REDUNDANCY MEASURES

Redundancy in a bridge system is generally defined as the ability of other members to help carry load when a member becomes weak or fails. The AASHTO Guide Specification for Fracture Critical Bridge Members penalizes nonredundant steel members. The bridge engineer is assigned the responsibilities of determining which members of the bridge must be classified as nonredundant and if the bridge system is sufficiently redundant. These are extremely difficult tasks, since no guidance is given in the AASHTO specifications concerning bridge redundancy evaluation. Presently, there are considerable differences of opinion about the definition of structural redundancy.

A review of both the deterministic and probabilistic system redundancy measures available in the literature is given in the following two subsections.

Deterministic Redundancy Measures

There are a number of definitions of deterministic measures of system redundancy *(14-17)*. These include:

- *Degree of indeterminacy*, (i.e., classical definition of indeterminacy used in structural analysis), I, defined as

$$I = F - E \tag{1}$$

in which F and E are the numbers of unknown reactive forces and of independent equilibrium equations, respectively. Unfortunately, this definition has no applicability in assessing the overall redundancy of a structural system which refers to the capability of the structure to carry load after one or more of its members have failed.

- *Reserve strength factor*, $R_{reserve}$, defined as

$$R_{reserve} = Q_{intact} / Q_{nominal} \tag{2}$$

in which Q_{intact} and $Q_{nominal}$ are the ultimate strength of the undamaged structural system and the nominal applied load on this system, respectively. However, to evaluate system redundancy one needs to cover the complete range of structural behavior from damage initiation until total collapse.

- *Residual strength factor*, $R_{residual}$, defined as

$$R_{residual} = Q_{damaged} / Q_{intact} \tag{3}$$

in which $Q_{damaged}$ is the ultimate strength of the damaged structural system.

A statically determinate structure would have no residual strength, $R_{residual} = 0$, after failure of any single component. On the other hand, failure of one component of a statically indeterminate structure will not necessarily constitute a complete loss of the load-carrying capacity for the structure (i.e., $R_{residual} > 0$).

- *Redundancy factor*, R, defined as

$$R = Q_{intact} / (Q_{intact} - Q_{damaged}) = 1/(1 - R_{residual}) \tag{4}$$

The redundancy factor R depends on the loading, the damaged members, the amount of damage in each member, and the material behavior of the damaged as well as of the intact members. The bridge redundancy factor correlates directly with the overall bridge strength in a damaged condition *(16,17)*. In general, the redundancy measure (R) ranges from a value of 1, when the structure has completely lost its strength (i.e., collapse), to ∞, when structural damage has no effect on the residual strength of the structure. It is interesting to note that in some cases of brittle behavior a damaged structure could have a higher ultimate strength than that of the intact structure (i.e., $Q_{damaged} > Q_{intact}$). In these particular cases of unexpected favorable behavior in the presence of damage, the redundancy factor R is negative. Examples of such cases were reported by Nakib *(18)*.

Probabilistic Redundancy Measures

The redundancy of a system has also a probabilistic nature. The availability of warning before total collapse occurs (i.e., system redundancy) depends also on the uncertainties in loads and strengths, correlations between member capacities and between loads, individual member failure probability levels, and structure configurations *(19)*. Several probabilistic measures of the redundancy of a system have been suggested in the literature *(16,20-23)*. These include:

- *Redundancy factor with respect to failure of the weakest member*

$$R_1 = (\beta_{collapse} - \beta_{weakest member}) / \beta_{collapse} \tag{5a}$$

or, alternatively,

$$R_2 = (P_{weakest member} - P_{collapse}) / P_{collapse} \tag{5b}$$

in which $\beta_{weakest member}$ = reliability index of the weakest member = min $(\beta_1, \beta_2, \ldots, \beta_i, \ldots, \beta_m)$ where m is the number of bridge members, $\beta_{collapse}$ = reliability index of the intact system with respect to collapse, $P_{collapse}$ = probability of collapse of the intact system, and $P_{weakest member}$ = probability of failure of the weakest member.

- *Redundancy factor with respect to any first-member-failure*

$$R_3 = (\beta_{collapse} - \beta_{first failure}) / \beta_{collapse} \tag{6a}$$

or, alternatively,

$$R_4 = (P_{first failure} - P_{collapse}) / P_{collapse} \tag{6b}$$

in which $\beta_{first\,failure}$ = reliability index of the intact system with respect to any first-member-failure, and $P_{first\,failure}$ = probability that any first-member-failure occurs in the intact system.

- *Redundancy factor with respect to a given damaged state of the system*

$$R_5 = \beta_{collapse} / (\beta_{collapse} - \beta_{damaged}) \tag{7a}$$

or, alternatively,

$$R_6 = (P_{damaged} - P_{collapse}) / P_{collapse} \tag{7b}$$

in which $\beta_{damaged}$ = reliability index of the damaged system with respect to collapse, and $P_{damaged}$ = probability of failure of the damaged system.

Observations

The computations of reliability indices in Equations 5a, 6a and 7a and probabilities in Equations 5b, 6b and 7b could be done by using modern system reliability techniques*(5)*. For the case of normal distributed variables

$$P_f = \Phi(-\beta) \tag{8}$$

where P_f is the probability of failure with respect to a given limit state, β is the reliability index with respect to the occurrence of the same limit state, and $\Phi(\cdot)$ is the normal cumulative probability distribution function.

It is interesting to note that

$$\beta_{first\,failure} \leq \beta_{weakest\,member} \tag{9a}$$

or, alternatively,

$$P_{first\,failure} \geq P_{weakest\,member} \tag{9b}$$

because initial failure can occur in any of the several bridge members. Consequently, for nonnegative reliability indices with respect to all limit states considered (i.e., $P_f < 0.5$) we have $R_1 \leq R_3$ and $R_2 \leq R_4$. For a statically determinate system the probability that any first-member-failure occurs is equivalent to the probability of system collapse (i.e., $R_3 = R_4 = 0$). The probabilistic redundancy measure R_5 varies within the range between zero and ∞, with $R_5 = 0$ indicating catastrophic effect of damage (i.e., $\beta_{damaged} = -\infty$ or, alternatively, $P_{damaged} = 1$) and $R_5 = \infty$ (i.e., $R_6 = 0$) indicating no effect of damage on the reliability of the structure (i.e., $\beta_{damaged} = \beta_{collapse}$ or, alternatively, $P_{damaged} = P_{collapse}$).

The redundancy measures R_1, R_2, R_3, and R_4, could be used in bridge design and R, R_5, and R_6, in bridge evaluation. It is important to note that these latter factors could also be used in damage tolerant bridge design, where redundancy is desired to ensure an acceptable bridge residual reliability level in case of unexpected damages.

AN APPLICATION EXAMPLE: COLORADO STATE BRIDGE E-15-AF

Bridge Description and Modeling

The example bridge used for this study is the Colorado State Bridge E-15-AF described by Nakib*(18)*. This bridge is a 90ft single span structure with a width of 36ft. It consists of a concrete deck with a thickness of 8.5in supported by four steel girders spaced at 9ft apart. Concrete and steel stress-strain relationships are given in Nakib*(18)*. The bridge is analyzed until failure using the Abaqus Multipurpose Finite Element Program*(25)*. The concrete deck is modeled using 143 quadrilateral shell elements, while each of the four girders of the bridge is modeled using 39 two-noded beam elements (i.e., 13 elements for the bottom flange, 13 for the web, and 13 for the top flange). The total number of degrees of freedom within the finite element bridge model equals 1794. The interaction between girders and deck is accounted for through the three-dimensional finite element modeling. The applied loads include dead loads D (weight of concrete deck and girders), live loads L (two HS-20 trucks applied side by side on the deck in order to induce maximum stresses in the bridge) and impact loads, I .

The detailed description of the geometrical and mechanical properties of the bridge, the finite element modeling, the uncertainties in loads and strengths, and the side-by-side position of the two HS-20 trucks which induce maximum stresses in the bridge are given in Nakib*(18)*. The live and impact loads are incremented progressively by the factor λ until reaching collapse.

Damage Models

The effects of damage on the redundancy of the Colorado State Bridge E-15-AF were evaluated using two damage models: (a) corrosion damage, and (b) accidental damage. In modeling corrosion damage a uniform loss of material in the exposed surface of the girders is considered. A uniform corrosion damage factor is defined as

$$D.F. = (A_i - A_d)/A_d \tag{10}$$

in which A_i and A_d are the cross sectional areas of the intact and damaged (i.e., corroded) girders, respectively. In modeling accidental damage one or two girders are completely removed from the bridge system. The program Abaqus*(25)* is used to determine the response of the bridge at different corrosion and accidental damage levels by increasing progressively the live and impact loads until total collapse of the bridge. Both the redundancy and reliability of this bridge were calculated for each damage scenario considered.

Deterministic Results

Inelastic load-deflection bridge responses under dead (D) and incremental (i.e., λ) live (L) and impact (I) loads, for various corrosion damage factors and accidental damage scenarios were obtained and the results are shown in Figures 1 and 2. Figure 1 illustrates the effect of corrosion damage, while Figure 2 shows how the removal of one or two girders affects the response of the bridge system. Deterministic bridge redundancy factors (see Equation *(4)*)

$$R = \lambda_{intact}/(\lambda_{intact} - \lambda_{damaged}) \tag{11}$$

were calculated for both damage models. In Equation (11) λ_{intact} and $\lambda_{damaged}$ are the ultimate load increment factors for the intact and damaged bridge, respectively. The redundancy factors R for corrosion and accidental damage states are indicated in Tables 1 and 2, respectively. The effects of corrosion on bridge redundancy depend on the rate of girder section loss. For example, a corrosion increase from 25 to 50% decreases the bridge redundancy factor from 3.13 to 1.54. A further increase in corrosion to 75% results in R = 1.02 (see Table 1). On the other hand, the damage caused by removal of one internal girder results in the redundancy factor R = 2.43, while removal of the two internal girders reduces drastically this redundancy factor to R = 1.34 (see Table 2).

Probabilistic Results

The effects of both damage and mean load multiplier (i.e., λ) on the bridge reliability index β are shown in Figures 3 and 4. For example, for λ = 1, Figure 3 shows that a 25% corrosion damage factor results in shifting the bridge reliability index from β_{intact} = 4.75 to $\beta_{damaged}$ = 3.40 and, consequently, the probabilistic bridge redundancy factor from $R_S = \infty$ to R_S = 4.75/(4.75 - 3.40) = 3.52, whereas 50% corrosion results in a lower bridge reliability, $\beta_{damaged}$ = 1.35, and, consequently, a lower probabilistic bridge redundancy factor, R_S = 4.75/(4.75 - 1.35) = 1.40. On the other hand, also for λ = 1, Figure 4 shows that removal of one internal girder shifts the bridge reliability index from β_{intact} = 4.75 to $\beta_{damaged}$ = 2.60 and, consequently, the probabilistic bridge redundancy factor from $R_S = \infty$ to R_S = 4.75/(4.75 - 2.60) = 2.21, whereas removal of the two internal girders results in a lower bridge reliability, $\beta_{damaged}$ = 0.71, and a lower probabilistic bridge redundancy factor, R_S = 4.75/(4.75 - 0.71) = 1.18.

CONCLUSIONS

Bridge redundancy is desired to ensure an acceptable level of residual reliability in case of unexpected damages. There are a number of definitions for structural redundancy in highway bridges, ranging from that implied by the traditional degree of structural indeterminacy to more rational measures that take into account the complete range of nondeterministic bridge behavior from damage initiation to total collapse.

In this paper, both deterministic and probabilistic system redundancy measures are reviewed. These redundancy measures deserve more attention in the design and evaluation of highway bridges. Further research efforts must be made towards establishing qualitative and quantitative provisions for designing sufficiently redundant bridge structures. The measures of bridge redundancy reviewed in this paper and the damage- redundancy- reliability interaction demonstrated in the numerical example should contribute to assist designers and inspectors in determining redundancy in highway bridges.

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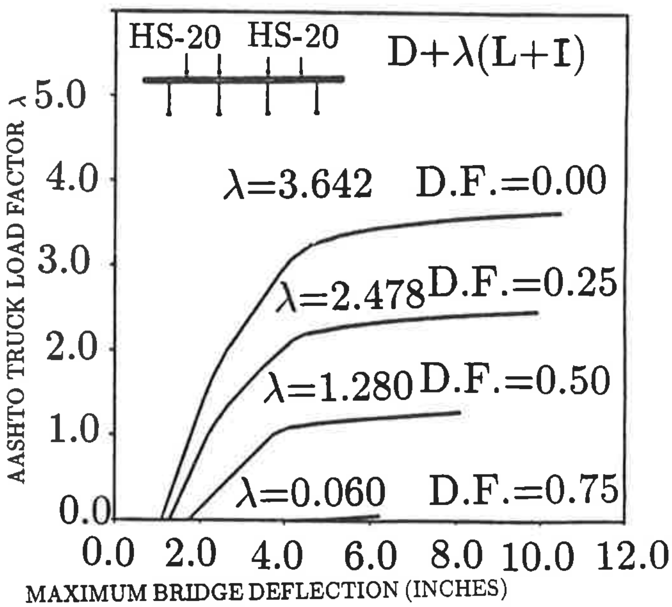

FIGURE 1 Load deflection response for corrosion damaged states.

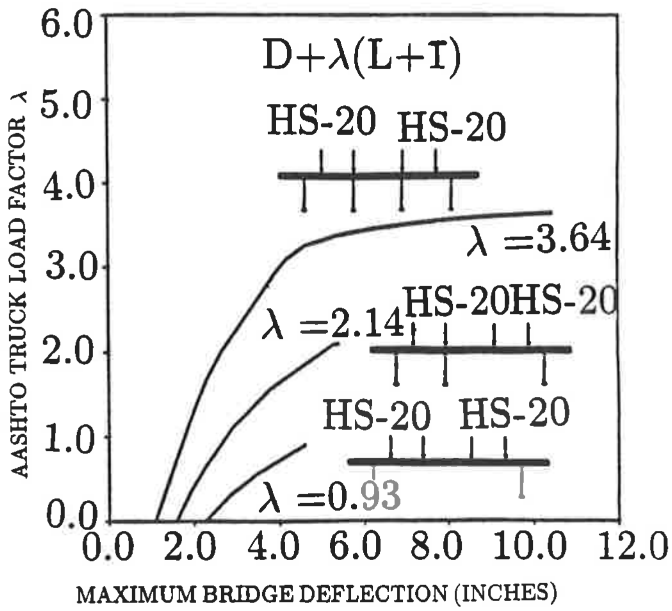

FIGURE 2 Load-deflection response for accidental damage scenarios.

TABLE 1 REDUNDANCY FACTORS UNDER CORROSION DAMAGE

Corrosion Damage Factor, D.F.	Load Increment Factors		Redundancy Factor, R 0
	λ_{intact}	$\lambda_{damaged}$	
0.00	3.64	3.64	∞
0.25		2.48	3.13
0.50		1.28	1.54
0.75		0.06	1.02

TABLE 2 REDUNDANCY FACTORS UNDER ACCIDENTAL DAMAGE

Accidental Damage Scenario	Load Increment Factors		Redundancy Factor, R 0
	λ_{intact}	$\lambda_{damaged}$	
Intact Bridge	3.64	3.64	∞
One Internal Girder Removed		2.14	2.43
Both Internal Girders Removed		0.93	1.34

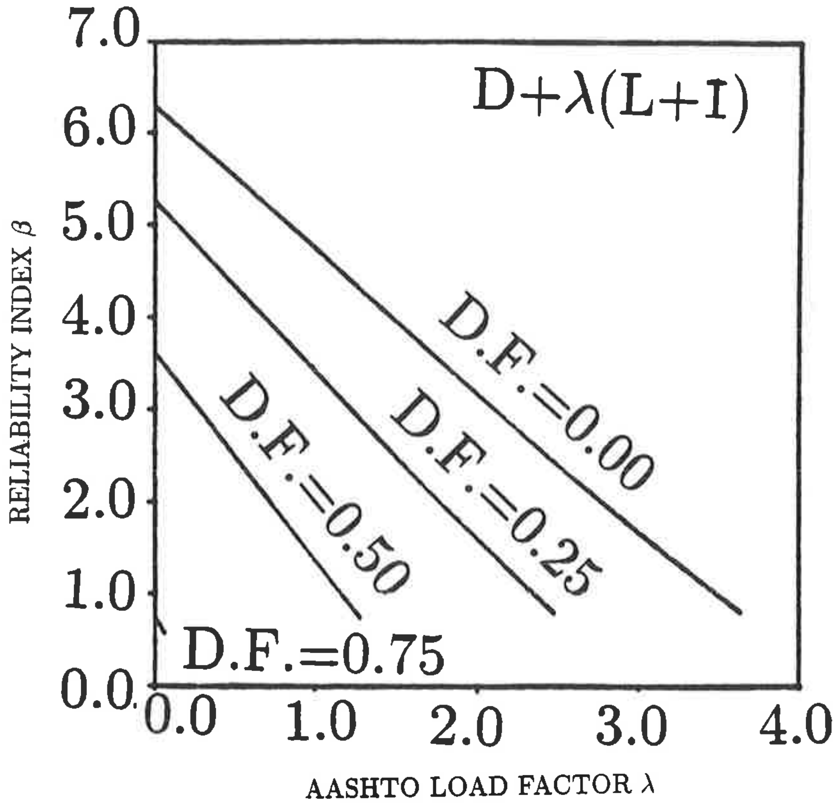

FIGURE 3 Bridge reliability index under incremental loading and corrosion damage states.

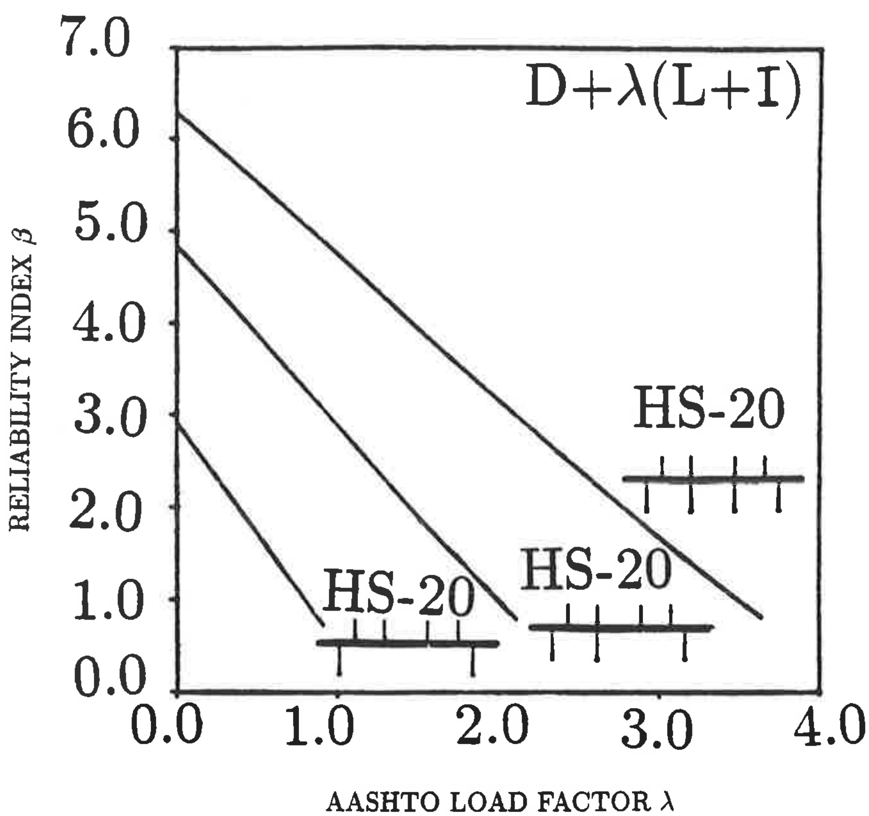

FIGURE 4 Bridge reliability index under incremental loading and accidental damage scenarios

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