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Reliability-based progressive collapse analysis of highway bridges

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ABSTRACT

Structural systems optimized to meet member design criteria as specified in current design standards and specifications may not provide sufficient levels of robustness to withstand a possible local failure following an unforeseen extreme event. In fact, the failure of one structural element may result in the failure of another creating a chain reaction that might progress throughout the entire structure or a major portion of it leading to catastrophic collapse. To reduce the chances of such collapses, the U.S. General Services Administration (GSA) established a set of procedures and criteria to evaluate the robustness of buildings using traditional deterministic methods. Although widely accepted and used for the progressive collapse analysis of buildings, the GSA criteria may not be suitable for bridges because of the differences in their structural configurations and in the nature and intensity of their permanent and transient loads. Furthermore, it is not clear how the existing criteria take into consideration the large uncertainties associated with estimating the applied loads and the capacity of structural systems to resist collapse following the initiation of a local failure. Because performing direct probabilistic analyses may be impractical for routine engineering practice, following current code calibration processes, design guidelines and standards can specify incremental progressive collapse analysis criteria that are calibrated based on structural reliability concepts to ensure consistent levels of safety for the pertinent range of applications, load levels and structural types and configurations.

The objective of this paper is to describe a methodology for performing probabilistic progressive collapse analyses and calibrating incremental analysis criteria for highway bridges accounting for the uncertainties in the applied loads and the load carrying capacities of the members as well as the system. The reliability analysis methodology is illustrated using models of a steel box girder bridge and a steel truss bridge subjected to different initial damage scenarios. The paper outlines how the results from several reliability analyses can be implemented to develop criteria that would lead to consistent levels of safety and reliability. Such criteria can, in the future, be used to propose progressive collapse analysis guidelines for bridges that are compatible with the principles of Load and Resistance Factor Design (LRFD) methods.

1. Introduction

Structural systems optimized to meet member design criteria as specified in current design standards and specifications may not provide sufficient levels of robustness to withstand a possible local failure following an unforeseen extreme event. In fact, local failure of one structural element may result in the failure of another creating a chain reaction of failures that progress throughout the structure leading to a level of damage disproportionate to the initial damage or to catastrophic collapse [1]. Progressive collapse occurs when a sudden local change in structural geometry due to the loss of load-carrying members results in dynamic forces exceeding the bearing capacities of the surrounding elements [2].

Catastrophic events, such as the collapse of the Alfred P. Murrah Federal Building in Oklahoma City in 1995, the World Trade Center towers in 2001, the I-35 W Mississippi River Bridge in Minnesota in 2007, and the I-5 Mount Vernon WA Bridge in 2013, have alerted the U.S. structural engineering community to the importance of ensuring structural survivability after an initial local failure. As a consequence of similar previous events, The Eurocodes (EC) documents EC 0 [3] and EC 1–7 [4] have emphasized the importance of designing structures to prevent damage to an extent disproportionate to the original abnormal loading event and the Federal Emergency Management Agency (FEMA) developed general guidelines for performing progressive collapse analysis [5]. Additional

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procedures and analysis methodologies are also provided by the General Services Administration [6], the Department of Defense [7] and American Society of Civil Engineers ASCE 7 standards [1]. These existing guidelines have been developed for buildings and may not be suitable for bridges because of the differences in the topologies and configurations of the two types of structural systems and in the nature and intensity of their permanent and transient loads. Furthermore, it is not clear how the existing guidelines and criteria take into consideration the large uncertainties associated with estimating the applied loads and the capacity of structural systems to resist collapse following the initiation of a local failure. Even though performing direct probabilistic progressive analyses may not be practical for routine engineering practice, it is widely accepted that level I criteria can be calibrated based on structural reliability concepts to ensure consistent levels of safety for the pertinent range of applications, load levels and structural topologies. This concept has been widely implemented in structural design practices under the label of Load and Resistance Factor Design (LRFD).

Progressive Collapse includes two types of loadings [8]: The primary load caused by a particular hazard or extreme event that may lead to an initial local damage. For example, exposure to hazards, such as pressures, impacts, or repetitive cyclic loads could lead to the sudden failure of an initial structural element. Secondary loads are generated due to the structural motions caused by the sudden failure of the damage-initiating element. The secondary loads are internal static and dynamic forces caused by sudden changes in the load path. Probabilistically, the progressive collapse process can be represented by the following equation [9,10]:

$$P(C) = \sum_{H}\sum_{D} P(C/D)P(D/H)P(H) \tag{1}$$

where $P(C)$ is the probability of system collapse, $P(H)$ is the probability of occurrence and intensity of hazard H; P(D/H) is the probability of local structural damage scenario, D, given the occurrence of the damage-initiating hazard H, and $P(C/D)$ is the probability of structural collapse given an initial damage scenario D. The probability of collapse is obtained by summing over all possible hazards and all possible local damage scenarios.

The goal of this study is to estimate P(C/D) which is the probability of structural collapse given a specified initial damage scenario D. The uncertainties in the damage itself is represented by $P(D/H)$ which along with $P(H)$ can be estimated using a combination of hazard and vulnerability analyses. The hazard and vulnerability analyses are beyond the scope of this study. The analysis of $P(C/D)$ is independent of H and it seeks to study the consequences of a given damage level on the integrity of the entire system. Naturally, $P(C/D)$ will depend on the type of loads and hazards that the damaged system is expected to carry. In this paper, damaged bridges are expected to safely withstand normal traffic loads independent of the damage initiating hazard.

The conditional probability of collapse term $P(C/D)$ is related to the analysis of the response of the bridge to a given damage scenario independently of what hazard led to the damage. Hence, the complement of $P(C/D)$ can be used as a reliability measure of the ability of the structural system to withstand local damage, which many researchers have defined as structural robustness [11]. Although the evaluation of bridge redundancy and robustness has been the subject of research for many years, previous studies have concentrated on the analysis of the reserve capacity of overloaded systems or investigated the ability of a damaged bridge to carry some level of live load in its damaged configuration (see for example [12,13]). The latter case assumes that the damage is incurred gradually without the release of energy that accompanies a suddenly occurring damage that may take place due to impulsive forces, fractures and collisions. For damage scenarios that involve the sudden failure of a structural member, the evaluation of $P(C/D)$ requires a three-dimensional nonlinear time history analysis of the structural system [14,8]. Well-designed structures under normal service load conditions should be able to survive such sudden failures without undergoing a disproportionate level of damage. The reliability analysis must account for the uncertainties in estimating the material properties, the permanent and transient loads applied on the structure when the initial damage takes place and the dynamic response of the structure due to the sudden failure of the initially damaged structural element.

Because performing advanced structural reliability analyses are impractical for routine engineering practice, structural design and analysis codes and standards have traditionally provided level I methods and criteria which allow design engineers to perform structural analyses supplemented with load and resistance (safety) factors calibrated to achieve consistent levels of reliability for the pertinent range of applications, load levels and structural topologies. Such Level I methods have been the basis of Load and Resistance Factor Design (LRFD) specifications and safety evaluation guidelines for bridges subjected to different types of loads and hazards. But, there currently are no similar guidelines for the progressive collapse analysis of bridge structures. This has led different engineering firms to develop their individual methodologies and criteria, which may lead to inconsistent conclusions regarding the safety of a particular bridge depending on who performs the analysis, what methodology is utilized, and which acceptance criteria are adopted.

The objective of this paper is to develop a methodology for calibrating progressive collapse analysis criteria for highway bridges accounting for the uncertainties in the applied loads and the load carrying capacities of the members and their propagation throughout the system. The reliability analysis methodology is illustrated using as examples a steel box girder bridge and a truss bridge subjected to different initial damage scenarios. The paper outlines how the results from several reliability analyses can be subsequently used to develop progressive analysis criteria that would lead to consistent levels of structural robustness and reliability. Such criteria can, in the future, be used by specifications developers to propose progressive analysis guidelines compatible with the principles of Load and Resistance Factor Design (LRFD) methods.

The proposed calibration process requires the following steps: (1) adoption of a structural reliability approach that is capable of handling complex structural systems with multiple modes of failure and low failure probabilities as described in Section 2 of this paper and implementing the approach for the progressive collapse analysis of bridge systems (Section 3); (2) probabilistic modeling of representative examples of typical bridge configurations that could be subjected to damaging events that may lead to progressive collapse (Sections 4 and 5); (3) modeling the loads on these bridges as explained in Section 6; (4) performing the dynamic reliability analysis of the systems due to the sudden removal of a structural element (Section 7); (5) applying the results of the dynamic reliability analyses to propose a set of analysis criteria that can be used in routine bridge engineering practice as described in Section 8.

2. Markov chain-based simulation method

The use of Monte Carlo Simulation (MCS), which is the most straightforward method for reliability analysis, is extremely inefficient when evaluating the probability of failure for complex structural systems because it involves the nonlinear analysis of systems composed of large numbers of random variables with many different modes of failure of low probabilities of occurrence. For this reason, researchers have developed various means to improve the efficiency of the simulation process. In recent years, two simula-