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Methodology for Risk Assessment and Management of Critical Bridges

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Abstract

An important aspect of designing bridges for security in an economically feasible way is to have in place plans for evaluating the criticality of any one structure on the transportation network. Thus, in deciding how to allocate resources, bridges considered more essential to the transportation infrastructure, or those thought to be at higher risk for a terrorist attack, should be given priority in the implementation of protective measures over other less critical bridges. This paper describes methods of carrying out threat and vulnerability analyses and risk assessments. Once the risks to a given bridge have been assessed, measures may need to be taken to mitigate these risks if they are deemed unacceptable. These measures generally attempt to prevent an attack by increasing surveillance or limiting access, but they can also include actions to limit the effects of blast loads or procedures to aid in rescue and recovery. Usually, deterrence and prevention measures will provide the least expensive solution to mitigate risk initially. Therefore, a risk manager should consider implementing these measures for short-term risks before strengthening a structure is specified. Deterrence and prevention, however, may not always provide the most cost-effective solution for long-term risks when considering life time costs, such as maintenance, replacement, personnel, and inspection costs.

Keywords: Bridge design, Risk management, Explosives, Blast loads, Risk Analysis

Introduction

Bridges are most important part of our transportation system as they boost the local and national economy through linking between two important places. It is also of strategic importance for military operations and proves as considerable national investment which is showcase of technical progress of nation. But there are some general problems arises during service life of bridges. Many bridges deteriorate due to aging, increased live loads, cracking, corrosion, environmental effects like freeze and thaw cycles and fatigue. Many bridges are structurally deficient or functionally obsolete. They need repair, rehabilitation or replacement. so there is need of rational bridge design codes, efficient procedure to evaluate actual load carrying capacity and actual loads on existing bridges, efficient methods for repairs and rehabilitation. There should be rational protective and preventive measures such as monitoring, maintenance and installation of security devices. Although this issue remains unfocused in past, there are few research institutes who did significant work in this area. This work includes reliability based design codes, load and resistance factor design(LRFD), Advanced FEM, Non-destructive evaluation techniques(NDT), Weigh-in-motion(WIM) measurement of trucks, Bridge Management system(BMS) and many more. The focus is on accelerated repair and rehabilitation of bridges.

Risk assessment

Structural designers and engineers need a method to identify credible threats, prioritize assets, and manage risk as designing or retrofitting all bridges to resist extreme loads is too expensive. Even though blast-resistant bridge design is a relatively new topic in the field of structural engineering, there are many state agencies and research organizations already have strategies for risk assessment and management. Although each approach differs slightly in implementation, all sources provide the same general guidance. This section highlights a risk assessment strategy based on a compilation of relevant sources,

and also provides a risk management method based on a comprehensive literature review. Publications by Abramson et al. (1999), Rummel et al. (2002), and SAIC (2002) provide valuable information regarding risk assessment and management. A report by Williamson and Winget (2005) outlines a comprehensive approach to risk assessment, and the method they propose is a compilation of the best practices found in the literature. fig 1 . shows stages in risk assessment for bridge security.
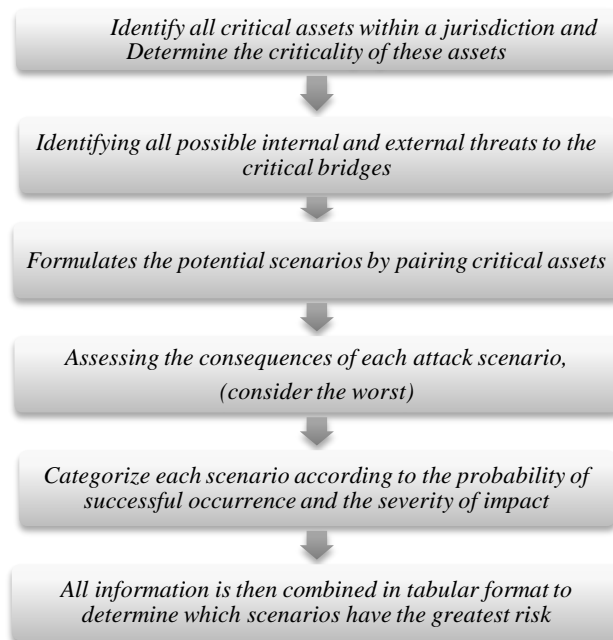
Fig 1 . Stages in risk assessment for bridge security

Step one of the risk assessment process is to identify all critical assets within a jurisdiction and determine the criticality of these assets based on function, average daily traffic, access to populated areas, access to emergency and medical facilities, military importance (Strategic Highway Network), importance to commerce, international border access, symbolic importance, availability of detours, presence of utility lines, and estimated repair time. The risk assessor should weight each criteria separately to reflect its importance within the jurisdiction, while not double counting for related criteria (e.g., average daily traffic may relate to major trade routes or availability of detours). This criticality score represents the importance of a bridge and indirectly captures the consequences of a potential attack (i.e., the consequences of an attack on a very important bridge likely will be great), and it is important to note that it should not include vulnerabilities to an attack or specific structural

weaknesses because a later step considers these issues. Additionally, certain criteria may warrant a placement of bridge in a higher importance category despite its overall criticality score. Examples include signature bridges whose failure may cause great socio-economic harm and bridges with significant military importance that have no detour capable of carrying the required traffic.

Step two consists of identifying all possible internal and external threats to the critical bridges identified in step one. Internal and external threats can be a variety of actions such as, the threat of earthquakes, high winds, or fire; however, the proposed risk assessment process only considers terrorist actions. Examples of potential attacks include, but are not limited to, a vehicle-delivered bomb on a superstructure, a vehicle- or maritime vessel-delivered impact and bomb against a column, hand-placed explosives between girders or inside box girders, or a series of timed events incorporating some or all of the above. As previously mentioned, designing a bridge to resist all possible threats is not feasible, and the risk manager should identify the most likely threat scenarios. Although terrorist activity is uncertain, a threat-point-of view analysis can provide insight on the most likely terrorist threats. This analysis considers factors such as the terrorists potential objectives, available resources, availability of targets, and the impact of a successful attack. Once all possible terrorist actions have been determined assuming that a terrorist has no limitations, each action should receive a score that indicates the relative probability of that action occurring compared to other actions. A multiplication decision matrix is best for this process, and the risk manager should conservatively assume that terrorists are experts in demolition, have structural engineering experience, and will encounter no resistance.

In step three, the risk manager formulates the potential scenarios by pairing critical assets identified in step one with potential threats identified in step two. Once scenarios are formulated, the process includes determining the probability of each event and assessing the vulnerability of assets with each scenario. Step four consists of assessing the consequences of each attack scenario, and the risk manager should assume the worst-case consequences of an attack not considering potential mitigation measures. Potential consequences include, but are not limited to, loss of life, severe injuries, loss of bridge function due to structural damage, and financial losses. Once each scenario (i.e., combination of threat

and asset) is identified, a risk manager should categorize each scenario according to the probability of successful occurrence and the severity of impact. The probability of occurrence is subjective and comes from the threat-point-of-view analysis, and the criticality score is the basis for the severity of impact.

Fig 2. Threat scenario categories (Williamson and Winget , 2005)

In final step all information is then combined in tabular format to determine which scenarios have the greatest risk and therefore require the most attention. An example of this table can be seen in Fig 2. Each scenario can be placed in one of the boxes based on severity of impact and probability of successful occurrence. Those bridges that fall in the severe and high range will receive the most attention.

Risk management
Once the risks are assessed, measures must be taken through a risk-management process to mitigate the risks to a level that is appropriate and economically feasible. Fig. 3 shows stages in risk management. The first step of risk management is to identify potential countermeasures available to mitigate the risks previously identified. Such countermeasures as deterrence, detection, or defense can reduce the probability of occurrence, while others can lessen the severity of the consequences through methods such as structural hardening, warning devices that indicate failure, or emergency operations planning. Additional considerations for selecting countermeasures include

resource availability, implementation difficulty, level of inconvenience, adverse environmental effects, adverse effects on serviceability, or usefulness.
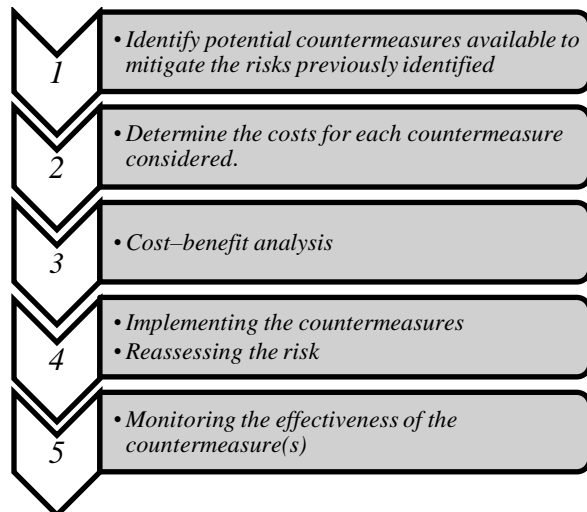

Fig 3. Stages in risk management

The second step of the risk-management phase is to determine the costs for each countermeasure considered. Cost considerations should include initial purchase, installation, maintenance, replacement, and service life. Step three consists of a cost–benefit analysis to determine which countermeasures would be the most effective and efficient. Williamson and Winget (2005) recommend that the benefits be in terms of risk mitigation achieved and that a countermeasure summary sheet be used. Because some countermeasures may also reduce other risks [e.g., fiber reinforced polymer (FRP) wrapping can reduce the risk of failure due to both seismic and blast events], the countermeasure benefits should be considered during the design process for all risks associated with the bridge under consideration in order to get a complete picture. The goal of step three is to ensure the maximum protection for all assets or the asset under consideration given the available resources. Prioritizing bridge importance may assist in allocating scarce resources among bridges. Step four consists of implementing the countermeasures and reassessing the risk with the countermeasures in place. If the countermeasures do not reduce the risk to an acceptable level, the scenario may require additional countermeasures, or senior managers will need to accept the risk to an asset until additional resources are available. It is important to note that no level of mitigation will completely eliminate all risk, and officials will need to determine the amount of risk they are willing to accept.

The fifth and final step of risk management is monitoring the effectiveness of the countermeasure(s) for future decisions and using this information to guide future risk-management decisions.

Characterization of analysis methods for blast-loaded structures

Blast prediction techniques are often separated into load determination and response determination methods, and both of these categories can be further divided into two groups:

- First-principle and
- Semi-empirical methods (National Research Council, 1995).

First-principle methods solve systems of equations based on the basic laws of physics. Accurate predictions of blast load and response can be obtained with these methods if the equations are solved correctly. Although first-principle programs use fundamental laws of physics and constitutive laws of materials, they have several limitations that are difficult to overcome without the use of empirical models. Blast propagation in real scenarios can be complicated by such things as atmospheric conditions, boundary effects, explosive material in homogeneities and rates of reaction, as well as many other parameters, and first-principle methods cannot easily account for these factors (National Research Council, 1995). Additionally, the calculation of changes in blast pressure due to large structural deformations and localized failures can be quite problematic because accurate constitutive equations for materials responding in this range are not readily available. Moreover, because of the highly nonlinear nature of structural response to blast loads, an analyst using first-principle methods to compute behavior should validate any predictions with actual experimental results to ensure that the methods are being implemented correctly. It can be very difficult, however, to find validated first-principle models due to a lack of experimental data available in the public domain, and any validation applies only to the specific scenarios that were experimentally considered (National Research Council, 1995). Despite these limitations, response predictions based on first-principle results can be developed when a lack of applicable data exist, but interpretation of the results requires engineering judgment and experience.

Semi-empirical models, in contrast to first-principle models, utilize extensive data from past experiments. As a result, they require less computational effort and are generally preferable over first-principle programs.

However, because a lack of experimental results for responses to blast loads exists in the public domain and because semi-empirical programs are only slowly becoming available to the general engineering community, structural engineers must often rely on first-principle methods and good engineering judgment to determine blast effects (National Research Council, 1995). In addition, semi-empirical models are often valid only for the structural members and scenarios considered during the formulation of the model.

Weighing the relative advantages and disadvantages of each modeling approach, semi-empirical approaches are always preferable because the models include validated empirical data. In fact, because of their efficiency over first-principle models for such cases, semi-empirical models are much better for design. For those cases in which the scenario in question relies on extrapolation of test data, or for cases where data are not available, first-principle models should be used by themselves, preferably after validation against experimental data or semi-empirical models for known cases, to predict blast loading and response. While the suggestions presented throughout this document address both first-principle and semi-empirical analysis methods, semi-empirical methods should be used whenever possible.

Some methods utilize both first-principle and semi empirical procedures (Winget, 2003). Equations first calculate blast-wave propagation and structural response, and the results are then compared to, and corrected by, empirical data from similar scenarios. These methods have wider ranging applicability than semi-empirical methods, and they require less computational effort and provide more accuracy than first-principle methods. Therefore, methods that utilize both first-principle relationships and semi-empirical data are very practical for design use. Although empirical data do not widely exist in the public domain, a few of these programs are available. The origin, accuracy, and applicability of the data used in these methods, however, may be difficult to verify.

Given that possibility, the guidelines presented in this document emphasize pure first-principle structural analysis methods over combined procedures, but an analyst should understand that legitimate techniques based on, or corrected by, legitimate empirical data are preferable over pure first principle methods at all times.

Most blast-analysis programs separate the calculation of blast-wave propagation effects from the determination of structural response. Thus, loads resulting from the chosen blast source are first calculated, and then they are applied to the structure using a separate response analysis method. Such separated methods are considered "uncoupled," and they typically provide conservative predictions of loads acting on structural components. Because the analysis typically assumes the structure is rigid during load calculations, structural deflections and localized member failures, which can vent and redistribute pressure, are neglected, and the analysis typically overestimates blast pressures and forces in unfailing members.

Accordingly, use of uncoupled methods often provides conservative load values for designing structural members. Coupled analysis methods, unlike uncoupled analyses, consider blast-wave propagation and structural response together as they interact over time. Thus, a structure can vent pressure through localized failure, and the forces resulting in many members will be smaller and more realistic than those predicted by uncoupled analysis approaches. For scenarios in which local failure or large deformations result, coupled analysis techniques may be necessary. Although coupled programs are expected to provide more accurate results than uncoupled ones, they do so at considerable costs due to the number of input parameters required, the time and experience needed to create a model and interpret the output, and the computational resources and time required to compute results. Because uncoupled analysis methods usually provide conservative blast propagation and structural response predictions, most design cases do not require the increased costs associated with coupled analysis methods.
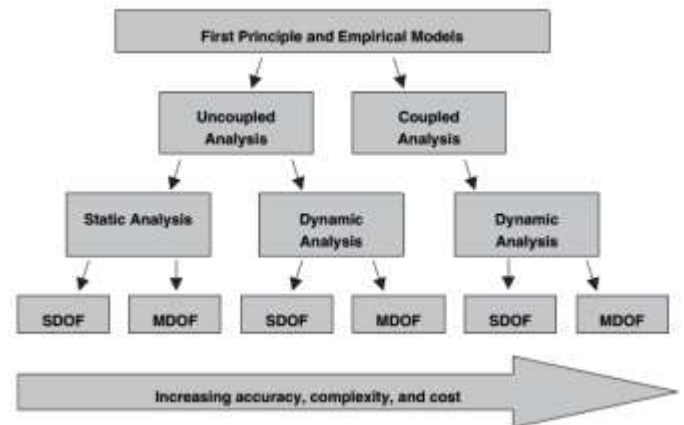

Fig 4. Flowchart of possible analysis methods (Winget, 2003)

Uncoupled and coupled analytical programs belong in two further subdivided groups based on the characteristics of the analytical methods employed. Uncoupled analysis methods have two categories: static analyses and dynamic analyses. Within each of those categories are single-degree-of-freedom (SDOF) models and multiple-degree-of-freedom (MDOF) models. Figure 4 and the following sections describe these divisions. It is important to note that the level of accuracy, computational time and cost, and complexity of analysis increase when moving from left to right in the figure. The next section describes further details, applications, and limitations of these methods.

A. Uncoupled Static Analyses

A static analysis for a blast scenario consists of an "equivalent wind design" (ASCE, 1997; Bounds, 1998), which is similar to the equivalent static procedure used for seismic design. Such an analysis can compute response for both single- and multiple-degree of-freedom systems. The approximated blast pressure under consideration is a static force applied to the structure being analyzed, and the analysis does not account for inertial effects. Because this method is very general, no program specifically exists for equivalent static blast analyses; however, those programs currently used for ordinary structural analysis can be used for this purpose. Although this method is relatively simple, its main weakness is accuracy. Unlike seismic events, vehicle impact incidents, or vessel impact scenarios, blast loading characteristics cannot be easily defined based on historical data. The loads acting on a structure for a given blast event can vary greatly depending on the type of explosive, the location of explosive, the

surrounding reflecting geometry, and the geometric and material properties of the structure being investigated. Accordingly, a static blast design requires the introduction of many approximations. In addition, no general equation exists to determine a conservative static load (Bounds, 1998), which makes determining an appropriate load for design is difficult (ASCE, 1997). Thus, accuracy is limited (ASCE, 1997; Bounds, 1998), and bridge designers should not use an equivalent static design for any purpose.

B. Uncoupled Dynamic Analyses
Dynamic uncoupled analyses vary from simple SDOF systems to more complex MDOF systems. SDOF dynamic analysis methods are relatively simple, and design engineers commonly use them to determine individual member response. The mathematical procedure required to derive the properties of the equivalent SDOF system is similar to that of a modal analysis used for seismic-resistant design. A separate load determination method can calculate the time-varying blast loading under consideration, and the SDOF analysis assumes a deflected shape for the response of the member being analyzed, often using a static loading response shape that approximates the dynamic response shape (Biggs, 1964; Department of the Army 1990). This deflected shape is then integrated along the length of the member with the actual mass and force to determine an equivalent mass and force for the dynamic system, and a simple spring-mass-damper system is then assumed and analyzed. The resistance used for the spring corresponds to the pattern of deformation for the member being analyzed. With this approach, the analysis of the SDOF model includes inelastic material behavior by noting the formation of plastic deformation mechanisms that correspond to the assumed displaced shape. For example, in a fixed–fixed beam under uniform loading, the bending moment acting at the supports will reach the plastic moment or section capacity as the magnitude of the load is increased. The analysis can include the plastic hinges that occur at the ends of a member by modifying the assumed deflected shape to account for the presence of the hinges. Such analyses can be solved in closed-form, but they often employ numerical solutions to allow for a wide range of loading histories and nonlinear material behavior.

Uncoupled dynamic analyses of MDOF systems can range from simple, dynamic 2-D frame analyses to very sophisticated 3-D finite element analyses. Models of the structural systems under consideration are constructed in commonly used analysis software,

and the time-varying load for the analysis comes from a separate load determination method. Because a category containing uncoupled dynamic MDOF analyses can represent a wide range of methods with varying capabilities, this document considers MDOF frame analyses and detailed finite element analyses separately.

C. Coupled Dynamic Analyses
Coupled analyses are intrinsically dynamic because they "couple" blast pressures with response to consider how the loading and structure interact over time. Sophisticated software currently available can model such complex fluid–solid interaction. When modeling MDOF systems, these programs allow the engineer to investigate global changes in response due to failure or large deformations of individual components. Although these methods can provide significant increases in accuracy over uncoupled analyses, they require a considerable amount of time to input the many variables needed to define such complex systems and perform the analyses. Furthermore, these analyses require a very experienced engineer to interpret the results. In addition, many codes claim to be coupled, but only a limited number of codes truly have the capability to couple blast pressures with structural response. For the vast majority of design scenarios involving blast loads acting on bridges, this level of accuracy is usually not necessary due to uncertainties that exist with blast loadings, and simpler analytical methods can often provide conservative and reasonably accurate results at a fraction of the cost (Winget, 2003).

Although conducting coupled SDOF analyses may be technically possible, doing so would not be practical because the results would not be very useful. If a model of a structural system and blast scenario requires a coupled analysis to account for expected load changes due to events such as venting from localized failures or large deformations, more than one degree of freedom would be necessary to investigate the change in response of one component due to the behavior of another component. Therefore, for all practical purposes, coupled analyses are useful only for MDOF models.

Risk ranking
Consideration of the relative risk associated with a range of inspection, maintenance and/or repair options can provide valuable information, particularly since decisions about specific bridge management activities are often made under the constraint of limited funds. Risk-ranking can be used

to evaluate various alternatives by comparing their relative risks (taking into account deterioration rates, relative frequency of overload, costs of failure, costs and efficiency of repair strategies, etc.). The focus of much of the most recent work in this area has been on the probability of corrosion initiation and/or corrosion effects (cracking, spalling, and delamination) rather than probabilities of collapse. Risk-ranking is appropriate only if the consequences of failure are similar for all bridges considered. Since delay and disruption costs associated with bridge repairs vary depending on traffic volume, a more meaningful measure is the expected cost of failure during the time period [t_1, t_2]:

$$E_c(t) = \sum_{i=1}^{M} \int_{t_1}^{t_2} \frac{f_T(t) C_F}{(1+r)^t} \, dt$$

where, r is the discount rate, $f_T(t)$ is the probability density function of time to failure t, and C_F is the failure cost associated with the occurrence of each limit state i. The precise definition of the term $f_T(t)$ is dependent on the context and scope of the decision analysis since in some circumstances it may be more appropriate to replace $f_T(t)$ with a conditional probability (such as a ''hazard function''). The failure costs can include both direct and indirect costs.

Since the expected performance (point-in-time probability of failure, expected residual life, etc.) of a bridge is assumed to vary with time, results from a risk-ranking procedure cannot be as stationary. Recommendations based on a comparison of relative risks may well change in time (e.g., as the bridge inventory ages and as management strategies are implemented). Stewart suggests, for example, that predictions of the effect of deterioration processes on bridge performance can only be viewed as being accurate for periods of 5–10 years. For that reason, it is suggested that risk-ranking only be performed for reference periods of this length or shorter.

Both optimal life-cycle costing and risk-ranking offer significant improvements over the more deterministic approaches forming the basis for many traditional bridge management systems. By coupling mechanics-based deterioration models with statistical models of loads and material properties in a probabilistic time-dependent analysis, important information about expected performance and relative risk, both as functions of time, can be obtained. This information can be used to make informed decisions about the inspection, maintenance and repair of the existing bridge inventory as well as about the design and construction of new bridges.

Conclusion

Risk-based approaches to bridge safety assessment for present conditions provide a meaningful measure of bridge performance that can be used for prioritization of risk management measures for maintenance, repair or replacement. The present paper presented a broad overview of the concepts, methodology, immediate applications and the potential of risk-based safety assessment of bridges. An application of risk-ranking was considered for illustrative purposes where it was shown that risk assessment should not be based on a condition assessment alone.

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