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Probability-based vulnerability and criticality assessment of a highway bridge subjected to terrorist attack

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ABSTRACT: Recent events around the world have brought into light the need to understand and assess the vulnerability of civil infrastructure systems to terrorist threats. While large signature structures may be highly vulnerable as symbolic targets, an attack on a non-redundant but less visible link in an inventory such as a railway tunnel has the potential to cause substantial casualties and economic and social disruptions. Yet it is not feasible to fortify and protect the entire inventory, and infrastructure owners must make decisions regarding how to best distribute their limited resources. This paper develops a probability-based method for quantifying the vulnerability of a public structure to attack and for ranking the criticality of the structure in its inventory by examining the consequences of such an attack. An illustrative example involving a highway bridge subjected to dynamic blast loading is presented.

1 INTRODUCTION

It has been motivated in existing literature that the transportation infrastructure of the United States is vulnerable to attack (see for example:(AASHTO 2002; SAIC/AASHTO 2002; AASHTO/FHWA 2003)). More specifically, it has been widely acknowledged that an attack on a strategic target can have massive structural, tactical, social, economic, and health consequences. Natural or accidental hazards (e.g. earthquakes and accidental vessel collisions) have been accounted for in the design process for quite some time, however the notion of considering intentional and malicious events (e.g. terrorist attacks) remains a relatively new concept. As a result, owners of transportation infrastructure have a new and well-founded desire – evident by the recent literature on the subject – to assess the vulnerability of the infrastructure within their jurisdictions to terrorist attacks. While various tools are currently available such as the prescriptive methodology prepared for AASHTO, (SAIC/AASHTO 2002) various shortcomings (e.g. over-reliance on subjective knowledge and a lack of quantitative analysis) have motivated the development of an alternate methodology proposed here. This proposed methodology incorporates many of the concepts introduced in(SAIC/AASHTO 2002), but offers a quantitative, probabilistic structural analysis based approach to assessment as a means to address shortcomings of previous work.

In this paper, we propose an assessment methodology to provide infrastructure owners with a rational means to compare and contrast the structural vulnerability of a bridge to terrorist attacks as well as a bridge's criticality with regard to other bridges within an owner's inventory. The most important outcome of the proposed methodology is the ranking of the vulnerability and criticality of structures specifically to terrorist threats based on various rational measures. While the discussion of the proposed methodology focuses on analysis of individual bridges within a jurisdiction, it can also be adapted to analyze "classes" of bridges for means of assessment. That is, an owner may choose to perform structural analyses of each bridge type (e.g. the owner may choose to perform analyses for short, medium, and long span steel bridges and then do the same for bridges of different spans and different types of concrete construction and so on) in their inventory rather than for each individual bridge in order to create time-savings. This may be desirable because bridge owners often favor a specific type of bridge and those structures are found throughout the inventory. However, while we motivate that structural analyses can be performed based on classifications, the consequence portion of the analysis should remain structure-specific.

This notion will be elaborated on in subsequent sections.

Any structural engineer with some level of familiarity with a specific bridge could list various ways that bridges could fail as well as potential worst-case scenarios to which a structure could be subjected. In a world of infinite resources, bridge owners would simply take this information and fortify their structures accordingly. However, bridge owners have limited resources that they can (or are willing) to dedicate to mitigating risks associated with terrorist attacks against their bridges. It is not financially feasible to overly fortify all bridges structurally. Unlike buildings, where a common way to mitigate threats is to use barriers, bollards, or other means to increase stand-off distances, it is obviously not possible for bridge owners to prevent vehicles from coming in close proximity to the bridge (or likewise tunnels or other forms of transportation infrastructure). Transportation infrastructure is open and accessible and understanding the risks to structures and knowing those structures most in need of actions to mitigate risks is an important concern of infrastructure owners. So, rather than mitigating each and every structure for the range of potential "worst-case scenarios" owners should make decisions based on the range of more likely outcomes for each structure given an attack. The proposed assessment methodology aims to provide infrastructure owners with a new tool for assessing and ranking those structures most in need of immediate action. This proposed methodology will allow owners to take into account the range of potential physical outcomes associated with terrorist attacks and to calculate the potential consequences of those outcomes. The synthesis of information regarding structural response and associated consequence measures will provide a means to assess and rank infrastructure vulnerabilities.

There is uncertainty associated with all issues relating to terrorist attacks ranging from the magnitude, location, and timing of potential attacks to the physical response or performance of the structure to an attack. Thus infrastructure owners must understand not only the potential threats, but also the expected response of their structures and the associated consequences.

Decisions regarding mitigation should first and foremost be based on the probability of a structure experiencing some catastrophic or unserviceable measure of damage. This propensity for experiencing damage can differ significantly from jurisdiction to jurisdiction (a caveat not necessarily comprehensively accounted for in "score and rank" prescriptive methodologies such as (SAIC/AASHTO 2002)). For example, designs for bridges in seismically active regions of the United States are held to very different design standards than those in seismically inactive geographic regions (Pekelnicky Presented: October 9, 2006 at the University of California-Berkeley). As a specific instance, the bridge columns in a seismic region are required to be able to resist strong lateral loads in addition to gravity axial loading (simple visual inspection will show that bridge columns in seismic regions are much thicker than those in non-seismic regions). Thus, given a blast event, which exerts three-dimensional pressures (lateral pressure against the columns as well as vertical pressures against the deck and girders), the columns designed to resist higher lateral load may perform better than those designed primarily for gravity loading. However, the exact benefits (and potential pitfalls) of seismic design standards on blast performance are a very new area of research. However, subjective assessment may not incorporate the importance of the differences between blast performances of 'differently engineered' bridges.[1]

2 PROPOSED ASSESSMENT METHODOLOGY

The goal of the proposed methodology is to present a non-prescriptive, yet consistent, and adaptable methodology that can be used to rationally differentiate between those locations within a transportation network more severely in need of mitigation and those that (because funds are limited) can be ignored or for whom mitigation efforts can wait.

Ideally we would seek a measure of expected damage as follows. Let T_i = Event that a terrorist attack of type i occurs (binary), I = random initiating event,[2] Ω = the set of random structural properties, D = damage to the structure, N = Number of attack types considered (e.g. blast event, vehicle/vessel collision), and C = Cost. We seek the distribution of damage, $F[D(I,\Omega)|T_i]$, the expected cost, $E[C(D)|T_i]$ and the measure of expected damage,

$$\overline{D} = \sum_{i=1}^{N} E\langle D(I,\Omega)\left|T_i\right\rangle P(T_i) \tag{1}$$

While many bridge owners are concerned with the vulnerability of their infrastructure, most, if not all, do not know the exact probability or likelihood that their structures will become the target of a terrorist attack because information and data regarding terrorists' motives, objects, and tendencies (measured

[1] Work has recently been performed in this area pertaining to buildings (Pekelnicky Presented: October 9, 2006 at the University of California-Berkeley).

[2] The random initiating event (I) describes the attack on a structure. Given that an attack of type i has occurred (say a blast from conventional explosives), I includes location of charge, type of explosive, peak pressure magnitude etc.

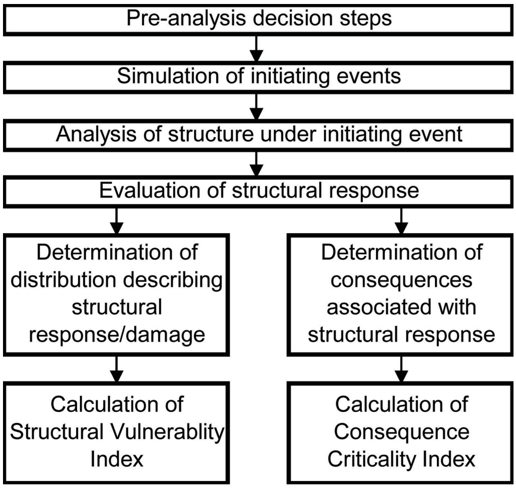

Figure 1. Methodological overview.

probabilistically) are not available.[3] Terrorist attacks are selective and can be directed strategically or at a "weak point" of a structure. Determination of the probability of an occurrence requires consideration of the motives of terrorists, and could be modeled using game theory. Because knowledge is not generally available to infrastructure owners about the motives of terrorists in order to utilize gaming strategy, we must necessarily perform conditional analyses. Instead, given no (or very little) knowledge of the probability of an attack occurring (the probability of an initiating event), the best infrastructure owners can hope to understand is the probability that a structure will experience damage given an attack. Thus, in Eq (1), we do not know the probability that an attack will occur, that is $P(T_i)$ is unknown, and we cannot calculate the unconditional expectation. As a result all subsequent moments and probability statements in this methodology are conditioned on the event that an attack occurs. Specifically, we concentrate on the conditional expectation $E[D(I,\Omega)|T_i]$ in Eq (1).

Of course if $P(T_i)$ ever becomes known or if use of a subjective value is desired, scaling by these probabilities and consideration of gaming strategy is possible. The use of conditional statements is not irrational as the event space of interest is necessarily the event space in which an attack occurs (that is, if we were not interested in this event space, then we would necessarily not perform the assessment). An overview of the methodology is presented in Figure 1. Details of each step will follow.

[3] Information pertaining to likelihoods of attack is either unavailable or limited in distribution due to security risks.

2.1 *Pre- analysis decision steps and analysis*

Prior to beginning the formal assessment, the analyst must first perform three pre-analysis decision steps. These three steps are likely the most subjective and difficult to perform, however they are integral to the assessment and consistency in these decision parameters must be maintained throughout the assessment (that is, they should not be altered during the assessment and if alteration is desirable, the assessment should be re-started at the top of the flowchart). The pre-analysis decision steps are:

1. The user must designate initiating events to be considered and designate probability distributions to describe the magnitude/severity of the initiating events. Examples of initiating events may include (individually or in combination): charge placement locations, blast pressures, deliberate vehicle/vessel collisions, load reversals, loss of girder cross-sectional area, or loss of cables in a cable-supported bridge. Several of the reports produced have offered guidance as to the types of attacks that should be considered viable (e.g. AASHTO 2002).
2. The user must designate a means to measure damage to the structure (structural models will later be used to quantify this damage measure and yield a probability distribution describing structural response). Examples of damage measurements may include: deflections, internal forces/stresses, energy method measurements, or loss in ADT (average daily traffic).
3. The user must define a relationship between the damage measure(s) chosen and the cost/ consequences of damage. An example of cost relationships may be repair/reconstruction costs associated with various deflections experienced by a structure as a result of an attack. However, in this step it may be desirable to include more than structural repair/replacement costs. This may include consequences associated with loss of life, economic costs, potential strategic consequences and so on. The consequences considered is based on the range of consequences the analyst wants to consider and deems appropriate. The relationship between damage and consequences is a difficult relationship to ascertain and may require much contemplation and debate.

After the three "pre-analysis" decision steps have been performed, the analyst may begin the formal assessment methodology. The first step after the pre-analysis decision steps involves Monte Carlo simulation of random attacks against the structure as well as random structural properties and model uncertainties. For each Monte Carlo trial, the analyst evaluates the response of the structure. The type of analysis performed can range from simple, linear-elastic analyses to complete second-order non-linear analyses that take into account dynamic effects (of course blast events are necessarily dynamic in nature). Traditional analysis packages may be used, the user may code his/her own analysis program, or explicit blast packages may be preferred. The analysis of structural response may include all relevant randomness in structural modeling and properties.

An appropriate metric of structural damage should have been carefully established in the pre-analysis decision steps, and the structural analysis results are used to determine the distribution of structural damage, $F(D(I,\Omega)T_i)$. For example, maximum mid-span deflection can be recorded and the data can be fitted to some well known probably distribution.

Once the structural response is quantified probabilistically and the associated damage cost/consequences quantified, the analyst should compute two indices used to rationally compare the urgency for action or mitigation steps regarding a specific bridge: the Structural Vulnerability Index (I_{SV}) and the Consequence Criticality Index (I_{CC})[4] as described in the following.

2.2 *Structural vulnerability index*

While a distribution can be quite helpful in understanding how a structure responds for the analyst, it may be more practical to have one single indicator that can be used to compare the structural responses of very different types of structures (something often much more valuable to decision makers who are removed from the formal assessment process). For that purpose, the proposed methodology calls for calculation of the Structural Vulnerability Index (I_{SV}). I_{SV} can be interpreted as an indicator of the potential for experiencing damage (vulnerability) given that a terrorist attack occurs. Mathematically, it is the weighted average of normalized damage measures and can be written:

$$I_{SV} = \sum_{i=1}^{n} \alpha_i \frac{E[\text{damage measure}_i]}{\text{Critical}[\text{damage measure}_i]}. \quad (2)$$

Where α_i is determined subjectively to reflect the relative importance of one damage measure versus another damage measure ($\Sigma\alpha_i = 1$) and n is the number of damage measures to be considered.

I_{SV} thus takes each damage measure (e.g. element stress) and normalizes it over some damage measure deemed to be critical (e.g. failure stress). For example, if we are again looking at nodal deflections, we might know from engineering experience (or formal analysis) that a nodal deflection of "x" number of inches indicates failure or a point at which the bridge is no longer serviceable. The importance of this relative relationship stems from the need to compare very different types of structures. For example, if a very short span bridge experiences a deflection of one foot that may indicate the bridge is beyond serviceability while a longer span bridge may have sufficient flexibility to remain serviceable under such a deflection. Thus we cannot directly compare the deflections of dissimilar bridges, but rather we must compare how close the bridge comes to failure (or how often is fails) as a way to compare the structural vulnerability of bridges across the inventory.

2.3 *Consequence criticality index*

For each simulated attack scenario, the consequences of the damage resulting from the attack can also be determined. The relationship between damage and consequences will have been determined in the pre-analysis decision steps and we call upon that relationship now. Mathematically, we derive $F(C(D)|T_i)$. At this point it is important to make the observation that many measures of consequence are hazard independent. That is, the importance of a bridge within a network is the same whether or not a terrorist attack occurs. For example, a network analysis (which may be a suitable means for determination of consequence) may show that a bridge is critical link in a network. The fact that the bridge is a critical link exists whether or not the bridge is ever attacked. Thus, any previous hazard analysis of bridges within an inventory (e.g. for seismic assessments) can be used as a resource in this step. Likewise, performance of this step will be a valuable resource for assessment of other hazards.

We may now interpret criticality, like vulnerability, as a measure of the consequence potential associated with damage to a structure. The Consequence Criticality Index (I_{CC}) is calculated based on the total costs (or individual cost components) of damage to or failure of a bridge. Unlike the Structural Vulnerability Index, which is based only on the damage to an individual structure, the Consequence Criticality Index is based on the costs/consequences associated with other bridges in the inventory relative to the individual bridge being assessed. We must remember that the purpose of this methodology is to compare and rank the vulnerability and criticality of an entire inventory of bridges. Letting $C_i(m)$ = cost component i of bridge m and β_i = a weight associated with the importance of cost measure i ($\Sigma\beta_i = 1$), the Consequence Criticality Index of bridge m in the system of p bridges is defined:

$$I_{CC}^{(m)} = \sum_{i=1}^{n} \beta_i \frac{E[C_i^{(m)}]}{\sum_{k=1}^{p} E[C_i^{(k)}]}. \quad (3)$$

[4] The notion of using "vulnerability and criticality" indices or factors as measures in an assessment are not unique to this paper though the specific definition and determination used here differs from previous work. See for example: (SAIC/AASHTO 2002).

As can be seen, I_{CC} provides a measure of relative loss to the owner/society given an attack. Or, more directly, it indicates how critical the loss of the structure is relative to other bridges in the owners' jurisdiction.

3 CASE STUDY

In order to illustrate the use of the proposed methodology, a rudimentary case study is presented. In this case study a user-created analysis algorithm is presented to illustrate (in simple terms) the use of a program written independently by the analyst (as opposed to using prepackaged structural analysis software) to perform the assessment. In order to perform a preliminary examination of the effects of dynamic loading on bridges, a simple MATLAB© (Mathworks 2003) algorithm was developed to model the imposition of a dynamic load (pulse excitation) on a simply supported structure. The scope of this paper is on presentation of an assessment methodology rather than on the formal analysis of structural response. As a result, computational issues are not the focus of this case study, which is presented for illustrative purposes.

The algorithm used for this case study performs linear-elastic, multi-degree of freedom dynamic analysis. It is a simplified model which includes approximation of blast loading as an equivalent triangular pulse (a relatively well-accepted approximation in practice). However, because non-linear response is not included and because other simplifications have been made, this case study should not be interpreted as a formal blast analysis or indicator of bridge response (calibration and verification has not been performed). A brief overview of this simple algorithm is presented in Figure 2.

We quantify our initiating event by three components: the location of the centroid of the attack along the main span (X_L) longitudinally, the location of the blast centroid vertically (X_D), and the amount of TNT equivalent in the explosive (E_{TNT}). Figure 3 shows the variables X_L and X_D as well as a schematic of the resolution of blast forces based on X_L, X_D and the blast magnitude, E_{TNT}.

It is assumed that the blast location parameters are uniformly distributed over the length and width of the bridge. This implies any location along the bridge has an equally probability of having the bomb placed below it. Of course, this very general assumption is based on a lack of knowledge about where a terrorist would likely place a bomb. More information regarding probable threat scenarios could yield a distribution with less entropy.

In this case study, blast magnitude is modeled using a triangular distribution based on information contained in (AASHTO/FHWA 2003). Assuming an industrial explosive is used and using a commonly

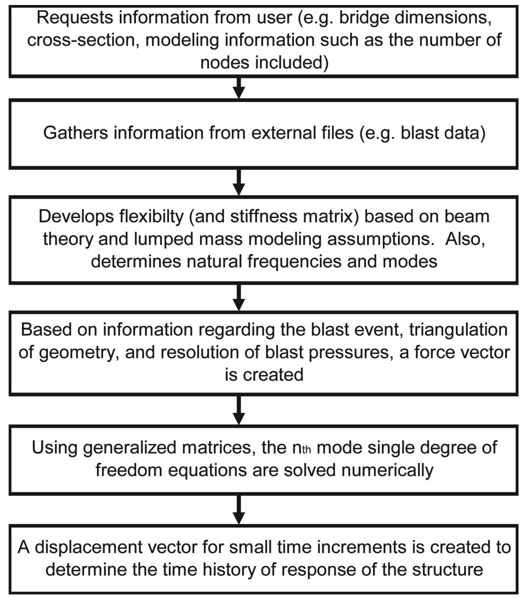

Figure 2. Algorithm overview.

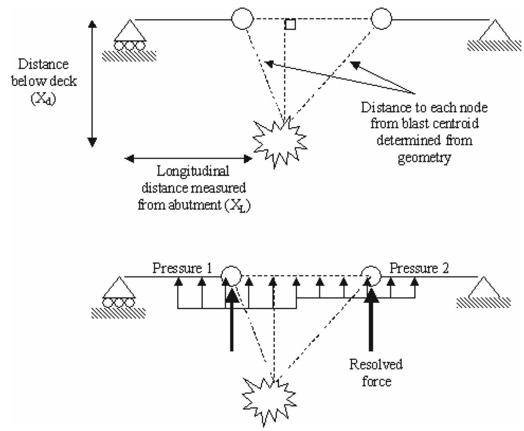

Figure 3. Schematic of random variables comprising blast event.

available method for calculating TNT equivalence (the details of which are not the scope of this paper but are available in many sources such as (Baker 1973; Kinney and Graham 1985))., we obtained a triangular distribution for blast magnitude.

In this study we measure damage based on maximum nodal displacements (δ_{max}) and the amount of deck damaged (D_d). Once again, damage is based on a deflection based criterion (rather than, for example, a stress based formulation) for ease in explanation and because the derived algorithm outputs nodal displacement in the time-history of response.

The California Department of Transportation provides comparative bridge costs to be used as "general guidelines for structure type selection and its relative cost." (California_Department_of_Transportation January 2005) Considering the CALTRANS estimation data we assume a cost of $180/ft^2 of deck damaged and the cost function for this case study is defined in the following equation:

$$\text{Total Cost} = \begin{cases} \sum_{i=1}^{n} \frac{a * c}{D} x_i \ , \text{ if } x < D \\ \\ F \ , \ \text{ if } x \geq D \end{cases} \tag{4}$$

Where:

x_i = Displacement at node i
n = number of nodes in the model = 5
a = Deck area attributed to each node = (11 ft^2)
c = Cost to repair ft^2 of deck = $180/ft^2
D = Critical displacement = 10 inches
F = Cost to replace the bridge (failure cost)
= area of deck * $180/ft2 = $526,320

Based on the information in the pre-analysis decision steps, we have decided that the initiating events will include the location of the blast centroid longitudinally (X_L) and vertical distance below the deck (X_D) as well as the blast magnitude (E_{TNT}). Next, Monte Carlo simulation was performed in which simulated draws of each variable were taken from the selected distributions (uniform and triangular as previously discussed). 100 simulations were performed and thus 100 values of X_L and X_D were selected from the uniform distribution. X_L was selected from a uniform distribution ranging from zero to the length of the bridge (43 feet) in integer values. X_D is assumed to be ranging from 9 to 12 feet below the deck in integer values.

After the initiating events were generated using Monte Carlo simulation, each initiating event was then applied to the structure and analyzed. We next analyzed the structure under each of the initiating events simulated and record the structural response by recording the maximum nodal displacements and maximum displacement (of any node) experienced by the structure.

Now that we have performed all the simulations and analyzed the structure under each scenario and calculated the costs of damage we can begin to analyze the results. The first form of analysis is determining a distribution of damage (structural response). That is, we derive $F(D(I,\Omega)|T)$.

The distributions of damage describing the structural response based on all the cases considered is presented below. The figure below presents a histogram of the maximum displacements experienced by the structure. The mean maximum displacement

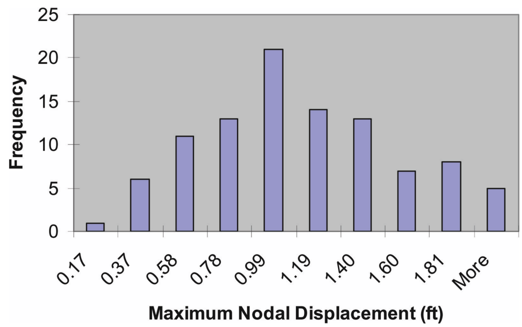

Figure 4. Histogram-maximum displacement (ft).

(out of the nodal maximums) was 12.2 inches (this is rather large due to the use of a linear elastic analysis).

We calculate the Structural Vulnerability Index in the same manner as discussed in the previously:

$$I_{SV} = \alpha_1 \frac{\overline{\delta_{max}}}{\delta_{max}^*} + \alpha_2 \frac{\overline{D_d}}{D_d^*} =$$

$$0.8\frac{12.2\text{in}}{10\text{in}} + 0.2\frac{2386\text{ft}^2}{2924\text{ft}^2} = 1.14$$

Where:

- α_i = weighting values
- mean maximum nodal displacement = 12.2 in
- critical value of maximum nodal displacement = 10 in ≈ L/50
- mean amount of deck damaged = 1381.2 ft^2
- critical value of amount of deck damaged = 2320.58 ft^2 = total area of bridge

Interpreting the Structural Vulnerability Index, we can conclude that, based on the attack scenarios/initiating events considered, this structure does not perform well. However, conclusions should always be based on comparisons with other structures.

For each Monte Carlo trial, we must determine the consequences of the damage to the structure. The relationship between damage and consequences had been determined in the pre-analysis decision steps and we call upon that relationship now. For each trial, we record the structural response. Using that structural response, we can determine the cost of damage for that trial using the defined damage/cost relationship.

The figure below presents a scatter plot of the maximum displacement of the structure versus total cost. As can be seen, there is a linear relationship when displacements are below a critical values and an asymptotic "plateau" showing the cases when displacement exceeded the critical value (total replacement).

Similar to the process described above relating to the distribution of structural damage, a distribution of costs should also be determined. Mathematically, we derive $F[C(D)|T_i)]$.

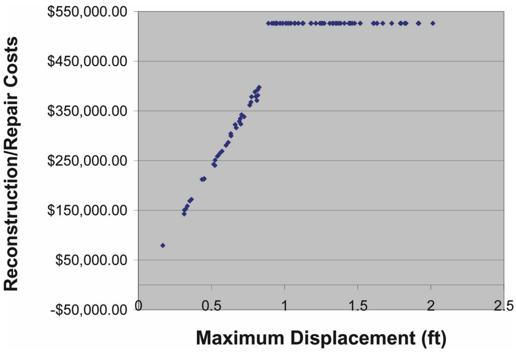

Figure 5. Scatter plot of costs vs. displacement.

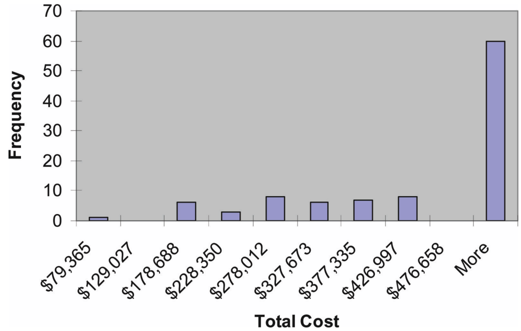

Figure 6. Histogram of total cost.

The figure below presents a histogram of total cost. The mean total cost for the structure was $429,474.

In this case study, once again for simplicity we only considered repair costs, however in an actual analysis it would be prudent to consider delay costs, consequence associated with loss of life, economic impact, symbolic value, importance as an emergency route, inclusion in the Strategic Highway Network, etc. However, providing guidance on these decisions is outside the scope of this paper. Thus when calculating the Consequence Criticality Index for this case study we consider only repair costs.

Table 1 shows a series of hypothetical average repair costs associated with bridges within the inventory in which this bridge is contained.

Based on the above tables, we can demonstrate explicitly the calculation of the Consequence Criticality Index in this case study though the costs are fabricated solely for use as an example. Noting that the sum of average costs is $8,914,114 and the average repair cost for this bridge is $429,474 we arrive at the following calculation.

$$I_{CC}^{(m)} = \sum_{i=1}^{n} \beta_i \frac{E[C_i^{(m)}]}{\sum_{k=1}^{j} E[C_i^{(k)}]}$$

$$= (1.0) * \frac{\text{mean cost of the structure considered}}{\text{total of average costs}}$$

$$= \frac{\$429474}{\$8914114} = 0.048$$

The Consequence Criticality Indices for each bridge are calculated in Table 1 and then the bridges are ranked according to I_{CC} (the bridge considered in this case study is the first entry in the table: Bridge #1). The table demonstrates that, while the high Structural Vulnerability Index of Bridge #1 indicates that the structure may not perform very well, when considering the consequences of failure, the bridge only has the 8th highest I_{CC} and thus has "less severe" consequences relative to other bridges in the inventory.

Table 1. Example costs, Consequence Criticality Indices, and rankings for hypothetical bridge inventory.

Bridge	Average replacement cost	Criticality index	Rank
1	$429,474	0.048	8
2	$526,896	0.059	5
3	$125,635	0.014	14
4	$345,685	0.039	9
5	$1,225,685	0.137	2
6	$895,635	0.100	4
7	$465,689	0.052	6
8	$265,761	0.030	11
9	$2,468,634	0.280	1
10	$165,798	0.019	12
11	$914,657	0.103	3
12	$123,689	0.014	15
13	$321,158	0.036	10
14	$462,976	0.052	7
15	$146,743	0.016	13

It should be noted that the priority ranking produced by the methodology and illustrated in this case study differs from rankings that may be produced for other hazards. Specifically, consideration of structural vulnerability is necessarily hazard-dependent as loadings inflicted on a structure during a malicious attack may differ significantly from natural hazards (e.g. load reversals). Calculation of the Consequence Criticality Index can typically utilize information from rankings associated with other hazards (e.g. earthquake), though for many jurisdictions, such as those not in seismic regions, such information may be unavailable. Additionally, though for simplicity only repair costs were considered in the case study, consequences associated with a specific structure and for different "attack scenarios" may differ for intentional hazards (e.g. social consequences).

4 CONCLUSION

Once the owner has both the Structural Vulnerability and Consequence Criticality Indices in hand, the owner has a means to directly compare vastly difference structures based on both the likelihood that the structure will fail given an attack (I_{SV}) and the relative consequence associated with damage to or failure of a structure (I_{CC}). While there are various methods currently available for assessing infrastructure (e.g.(SAIC/AASHTO 2002)), this proposed methodology diverged in several ways; most notably in that it provided a direct means to compare vastly difference structures as well as a less-subjective criterion upon which to make decisions.

The proposed methodology is based on the conjecture that decisions regarding mitigation of structures to terrorist threats should be based jointly on structural reliability and expected loss. For example, using the Structural Vulnerability Index, an owner may learn that bridge A is more structurally vulnerable than bridge B, however the losses associated with bridge B may be relatively higher than those associated with bridge A.

In order to reduce computational effort, a bridge owner may choose to perform the structural analyses for specific bridge class (e.g. pre-stressed concrete box girder bridges of medium length), derive a distribution of damage (and perhaps a formal statistical distribution fit to the data) that can be used to assess all bridges of similar classification. However, consequence analyses are unique to each bridge, thus consequence analysis can not be performed for bridge classes.

A case study was presented how to use the proposed methodology in general. The case study should not be interpreted as explicit evidence of the best or only way to model a structure nor should the results be interpreted as indicators of actual structural performance. Rather, the case study serves as an example of how analysts could model a bridge's structural performance under random attack scenarios, structural properties and model uncertainty. Future research is needed to best understand the best analytical tools available. However, such efforts are outside the scope of this paper. The reader may draw upon the case study as both an example of implementation of the proposed methodology as well as a "first cut" in tools available for analysis.

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