A Framework for Performance-Based Optimization of Structural Robustness

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ABSTRACT: The possibility of a local structural failure to propagate into a global collapse of the structural system has fueled the continued development of improved computational methods to model building behavior. In spite of these efforts, the recent past has witnessed numerous structural failures in response to extreme loading events resulting from both natural and man-made hazards. These incidents highlight the significant threat to our built environment posed by low-probability-high-consequence events that often induce an inelastic structural response and result in disproportionate damage relative to the initiating event. This paper examines the relationship between load and damage propagation for this unique class of hazards, speaking largely in the context of blast loads resulting from an explosive threat. Common state-of-practice engineering solutions in blast resistant design often strive to adapt conventional deterministic methods to incrementally strengthen a structure on an element-by-element basis, as needed, to address specific load concerns. The resulting design, however, is ill-equipped to cope with uncertainties in building geometry, load characterization, damage propagation, etc. that vary significantly from assumed initial conditions. This paper proposes an alternate performance-based framework to optimize structural robustness in the presence of uncertainties and better inform the decision-making process related to damage acceptance. The design process starts with the characterization of hazards and then calculates the resulting damage propagation and functional loss by deriving and, subsequently, balancing functional relationships between design and consequences. The proposed methodology can be implemented directly to complete performance assessments or can be used as a basis for establishing damage acceptance criteria and provisions to achieve resilient structural solutions.

1. INTRODUCTION

The recent past has witnessed unprecedented levels of structural failures in response to extreme loading events and structural deterioration. Despite engineers' efforts to implement an elevated level of design, these incidents have highlighted the significant threat to our built infrastructure posed by low-probability-high-consequence events and the shortcomings of conventional design approaches in providing an effective engineering process to confront failure propagation as part of the design process. Emerging trends in the engineering community suggest the problem is rooted in the misnomer of achieving a "collapse proof" structure using design approaches that address a limited range of performance in response to specific extreme loading conditions to incrementally increase resistance. The resulting design is often unable to cope with even slight variations from assumed initial conditions that affect estimation of local and global response of the structural system.

Given the need to preserve building functionality, designers are turning to concepts of resiliency, which stress the need for design that provides the ability for a system to resist, adapt to, and recover from exposure to a broad range of hazards. The resiliency of a system is measured by its ability to mitigate the effects of an extreme load and minimize the recovery needed to restore functionality. The concept of resilience is applicable at multiple levels within the scale of the built environment, progressing from individual components of single structures to networks of structures to entire communities. Evaluations of resilience at each level are critical to the overall ability of our infrastructure to withstand and recover from extreme events. The framework developed in this paper focuses on a single structure that experiences significant local damage in response to high-intensity blast loads and discusses resilience relative to the ability for global system to forestall disproportionate consequences.

This paper outlines a decision-based framework by which the magnitude of the consequences to blast-induced local damage can be calculated and used to assess structural resiliency. Current models define system resiliency as the time to full (or nearly full) recovery after a shock, insult or disturbance (i.e. hazards). In this context, it is difficult to understand the engineering process by which to evaluate and implement resilience. This paper proposes an alternate definition of resilience in which the amount of required recovery is correlated to the amount and severity of damage inflicted by an explosive event. In this framework, the user determines the likely damage for a range of increasing threats and decides whether the resulting sequence of damage and corresponding consequences is acceptable. Current performance-based methodologies are adapted to provide a procedural framework that is multi-deterministic and, therefore, more accessible to engineers who rely on the current state of practice. The mathematical formulation of the proposed approach is discussed, and a design example is provided, in which the proposed framework is demonstrated.

2. ROBUSTNESS AND RESILIENCY

The key issue confronted by collapse resistant design approaches is the formulation of a structural solution to resist an unexpected and unpredictable event without a priori knowledge of the location of the local damage and, thus, the load redistribution mechanism is a requirement. At the epicenter of progressive collapse theories and design practices is the concept of robustness. This quality of a structural system characterizes the extent to which stability can be maintained when equilibrium is perturbed. Collapse resistant design is essentially the practice of calculating structural robustness and enhancing the ability of the system to cope with extreme load conditions, where it is necessary.

Lacking clear guidance in how to achieve robustness, engineers have extended their understanding of conventional structural theories in the pursuit of collapse resistant design. The predominant technical methods employed in this exercise are deterministic in nature and rely on a series of assumptions to reconcile unknowns associated with damage scenarios, initial conditions that define system resistance, and observed variability in structural performance at the brink of collapse and provide an achievable path to implement collapse resistance. The design process is largely characterized by a component-by-component validation of the structure and subsequent local strengthening of the system until a prescribed level of resistance is achieved. This process is predicated on the assumption that robustness is a variable property of the structure, correlated to strength and load path redundancy. However, observed structural behavior in the aftermath of extreme loading events contradicts this assumption. There are many examples where seemingly highly redundant structures have failed and, conversely, where expected building failure was not observed.

This paper argues that the disparity between expected and observed building performance is rooted in the assumption that strength-based methods, applied at the component level, will adequately alter the global resistance from which structural robustness is derived. Rather than consider the resistance as a sliding scale in relation to a fixed load, the proposed alternative is to consider robustness as a fixed property of the system that is uniquely tied to the structural configuration as expressed in Eq. 1:

$$\mathit{Robustness} = f(\mathit{topology}, \mathit{geometry}) \qquad (1)$$

In this formulation of robustness, topology refers to the structural configuration relative to the site or location. This property defines the expected exposure of the structure to concentrations of extreme loads. The geometry term refers to the layout of the structural load bearing elements. Both are absolute properties that cannot be changed without modifications to the overall system (both location - topology and structural system - geometry) configuration. In this way, once the structural system location and geometry has been defined so too has its robustness.

If robustness is held to be an absolute property of the system, then resilience represents the variable property that fluctuates with specific design decisions. Pursuit of resilience is typically considered to be an exercise in balancing the ability of a given structure to resist, adapt to, and recover from extreme events (see Eq. 2). The resistance component of Eq. 2 represents the engineering effort to withstand a prescribed hazard. Load resistance allows the structure to rapidly recovery to a wide range of threats by avoiding damage. However, even robust structures may experience some damage when subjected to extreme loads. To resist blast loads, structural elements are designed to experience allowable levels of plastic deformation. Even if element failure (i.e. collapse) is avoided, damaged elements will require repair or replacement, resulting in a temporary loss of functionality. Resistance should, therefore, be provided such that potential damage minimizes casualties and reduces the likelihood of catastrophic structural losses. The adaptation component is largely understood to consist of high-level emergency planning efforts to restore function in the aftermath of a catastrophe. The recovery component represents the process over time in which system function is restored via repair and/or replacement. The perceived balance of these variables, as it impacts system resilience is visually depicted in Fig. 1, which plots functionality on a time scale.

$$\begin{aligned}\mathit{Resilience} &= \\ &= f(\mathit{resistance}, \mathit{adaptation}, \mathit{recovery}) \quad (2)\end{aligned}$$

Eq. 3 revises the common expression of resilience to exclude the recovery and adaptation components, as these parameters cannot be easily and directly quantified as part of engineering design efforts. The resistance component of resilience is broken into robustness and hazard parameters.

$$\begin{aligned}\mathit{Resilience} &= f(\mathit{hazard}, \mathit{robustness}) = \\ &= f(\mathit{hazard}, \mathit{topology}, \mathit{geometry}) \quad (3)\end{aligned}$$

In this modified expression of resilience, the structural performance associated with a specific system configuration is considered to be independent from the contribution of component strengthening to address a prescribed load or hazard. The resulting equation for resilience represents the specific hazard magnitude mitigated by a structural design with an assigned robustness. This definition of resilience allows engineers to quantify resilience and robustness in more certain terms and provides a basis to better assess post-event structural behavior.

3. PROPOSED FRAMEWORK

The proposed framework is centered on a performance-based calculation of the consequences due to blast-induced local damage. As a starting point, a risk-based integration is constructed to calculate the likely magnitude of consequences in terms of system topology and geometry. The methodology is based on the total probability theorem, similar to that used by several performance-based approaches (Barbato et al. 2013; FEMA 2012):

$$C(T) = \iint G(DM \mid IM) \cdot DM(IM) \cdot dDM \cdot dIM \quad (4)$$

Where:

DM(IM) is the cumulative probability of damage *DM*, given the intensity measure *IM* and represents the topology function for the system. The topology function informs about expected damage due to the certain event. Multiple events can be included using numerical simulation techniques.

G(DM|IM) is the cumulative probability of consequences (total collapse) given the damage *DM* and represents the geometry function. The geometry function informs about the structure's ability to absorb localized damages as identified in the topology function.

The multiplication of the topology and geometry functions will result in a surface plot, representative of the system's robustness, that can be qualitatively and quantitatively assessment. For instance, sudden changes in slope and peaks may represent stable solutions. Detailed analysis of the robustness surface may enable optimization of the structural system relative to specific performance objectives. The optimization process includes balancing the following quantities:

1. Expected damage as identified by topology function
2. Structures ability to sustain and recover from the damage
3. Cost associated with the acceptance of the damage.

Integration of the robustness surface is, ultimately, needed to develop solutions that address the full range of threat scenarios (size and location) and associated damage.

4. CASE STUDY

A simplified design example is provided to illustrate the implementation of the proposed resilient framework in the context of blast-resistant bridge design. This example demonstrates the process by which resilience can be assessed and high-level design decisions can be made to select optimal structural system configurations as part of early design stages where a fixed threat is considered.

4.1. Topology Function

The prototype bridge structure used to illustrate the proposed framework is shown in Fig. 1. Bridge failure models associated only with cable losses are considered to simplify the case. The cables are numbered sequentially and all cables are assumed to be characterized by the same material and section properties. This assumption allows cable damage to be determined as a function of distance relative to the blast origin. That is to say, all cables will experience the same damage in response to a given blast load intensity. In practice, accounting for variable element design and failure models would be required to accurately determine the sequence in which failure propagates from one cable to the next given the IM distribution.

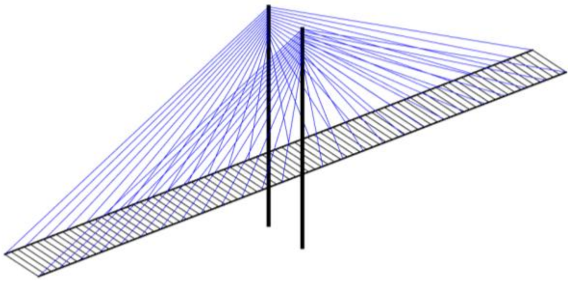

Figure 1: 3D model of a bridge

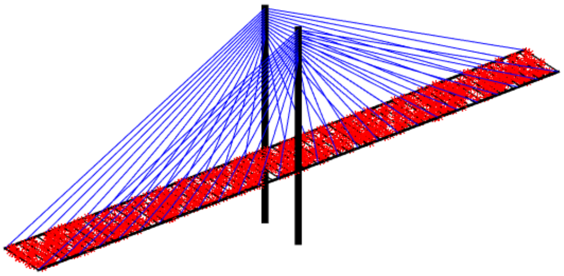

Figure 2: 1000 threat scattered at bridge deck

4.2. Geometry Function

For the purpose of this example, we assume that the bridge is designed to sustain the loss of two consecutively located cables. If the loss extends beyond two consecutive cables, the bridge will

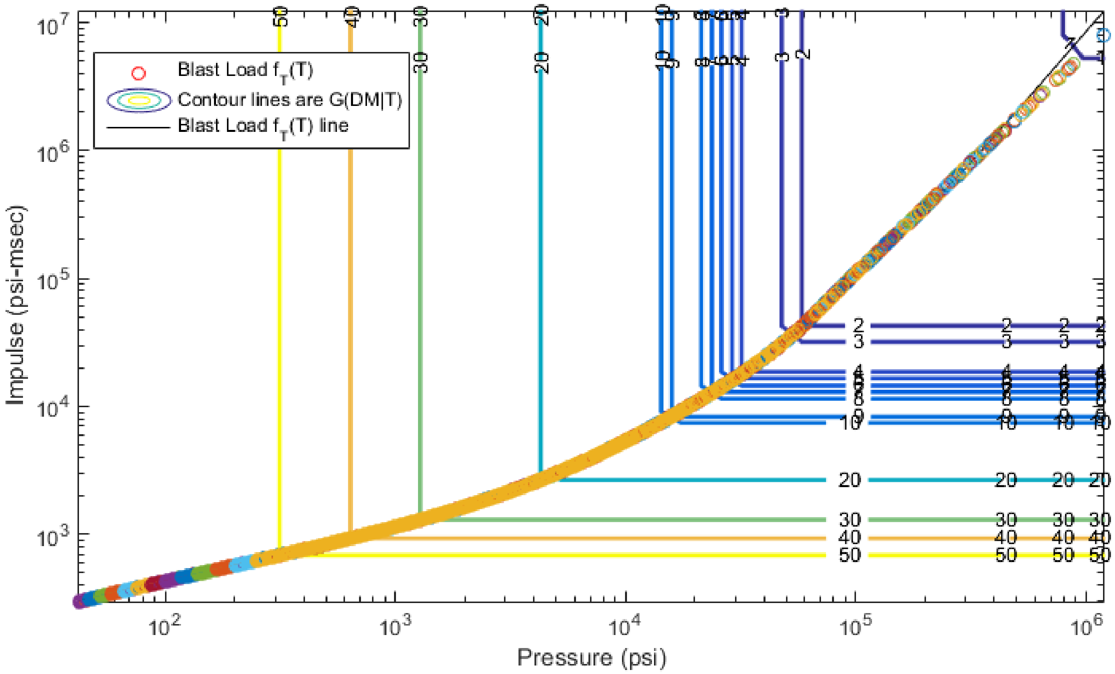

Figure 3: Hazard Intensity Measure (IM) scatter plot for each cable for all threats

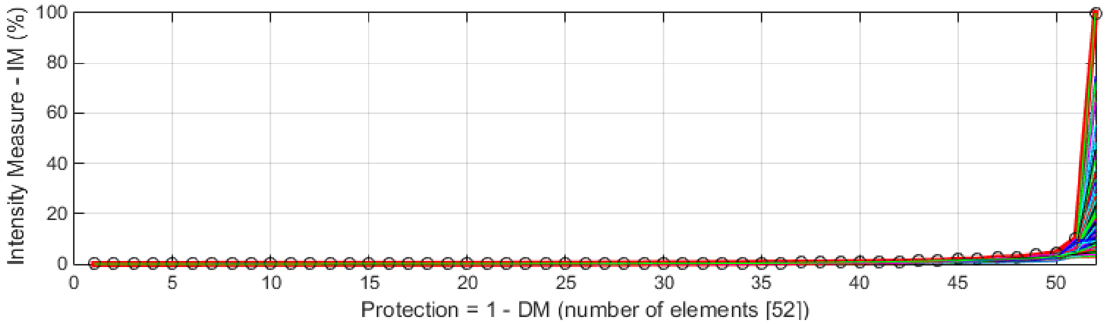

Figure 4: Topology plot of relative Intensity Measure (IM) Plot for All Cables

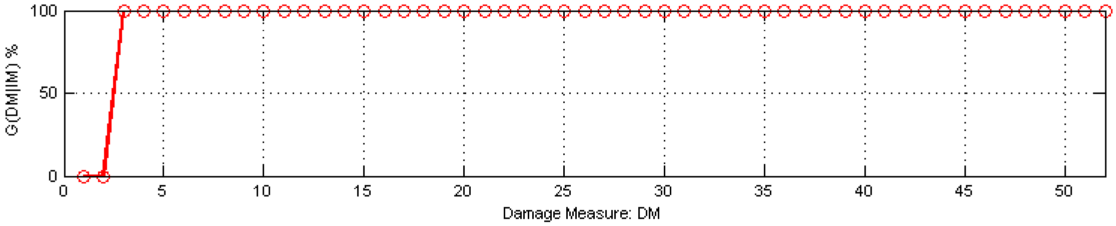

Figure 5: Geometry plot of Consequence Function

collapse. Stated differently - the acceptable damage is the failure of two cables.

4.3. The Sequence of Damage

Given the assumption that all cables are equal, cables with the greatest exposure to extreme loads are considered to also experience the greatest extent of damage. In this way, the example establishes a direct correlation between the *DM* and *IM* components of the mathematical formulation and simplifies the process of assessing damage propagation. As shown in Fig.

4, for instance, only 1 cable is expected to experience the highest loads and incur the greatest levels of damage. In practice, the *IM* field can be used to assess damage on a component-by-component basis to establish a design-specific correlation between the *DM* and *IM* parameters.

4.4. Damage and Consequence Functions

In general, the consequence function can be derived by rigorous finite element analysis of the structure to assess damage propagation given a sequence of element failures. However, for the purposes of this example, the consequence function is derived empirically based on the number of lost cables. In this way, failure of an individual cable can be deterministically correlated to a structural loss measure. Each consequence function is unique not only to the structure but also to threat location.

Fig. 5 illustrates the consequence function for the bridge. Failure of less than two cables is assigned a consequence of zero. If cable loss exceeds 2, the consequence is set at 100% (i.e., total collapse of the bridge).

5. CONSEQUENCE AND ROBUSTNESS

An overall consequence measure (*CM*) can be obtained by multiplying the consequence function (*C*) of Fig. 5 with the plot of relative *IM* portrayed in Fig. 4, which is directly correlated to the Damage Measure (*DM*) for this example. Fig. 6 shows the *CM* surfaces for example bridge structure for selected threat location over the domain of *IM* and *DM*. The consequence *C(T)* is then obtained by calculating the volume under each surface

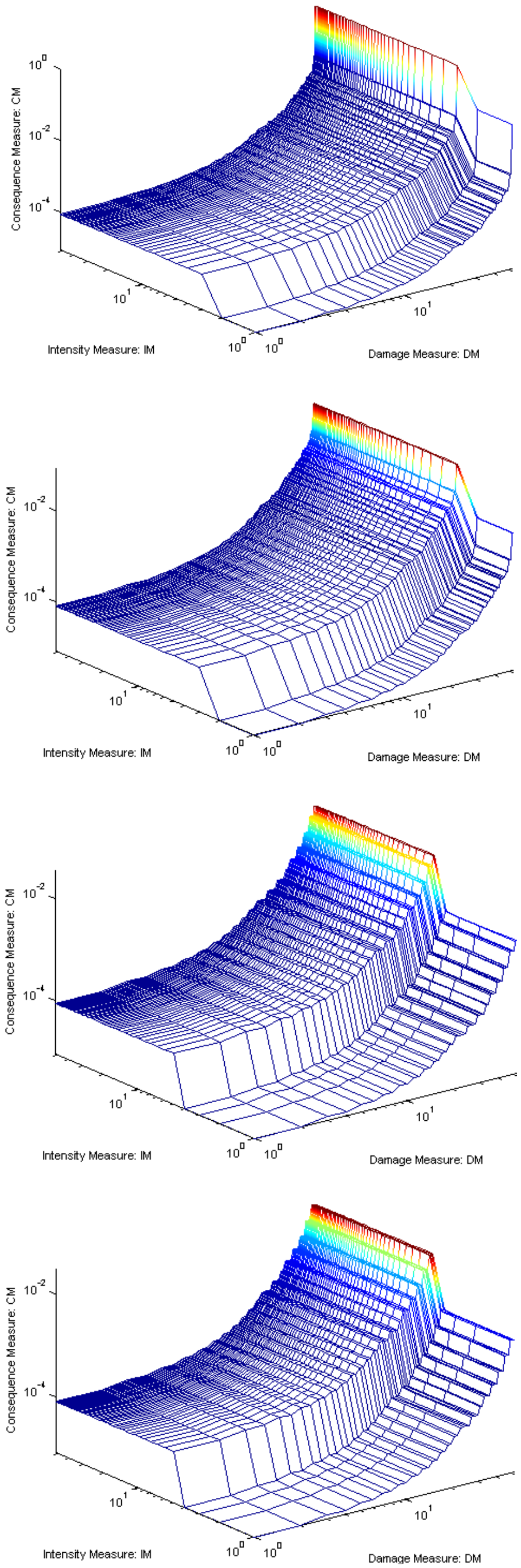

Figure 6: Robustness surface for selected threats

6. CONCLUSIONS

This paper outlines a decision-based framework by which the magnitude of the consequences to blast-induced local damage can be calculated and used to assess structural resiliency. The procedure for resiliency assessment starts with the characterization of hazards and calculates the resulting damage modeling and functional loss by deriving and subsequently balancing functional relationships between design and consequences. The outcomes of each process are articulated through a series of generalized variables, termed as topology, geometry, and damage and hazard intensity measures. The framework is multi-deterministic and, therefore, more accessible to engineers who rely on the current state of practice. A design example using a cable-stayed bridge was used to demonstrate the implementation of the framework.

The proposed framework has potential to be adapted for other hazard types such as impact or fire exposure that, like blast, are typically characterized by concentrated intensities. To address these additional hazards, future work is needed to develop methods to calculate the spatial distribution of hazard intensity and characterize the resulting damage and consequences. Adapting this procedure for impact loads would be fairly straightforward since most elements that are affected by the impact could be evaluated on a pass-fail basis similar to the use of performance criteria for blast load. Including fire exposure poses a greater challenge since elements with thermally induced material weakening and restraint of thermal expansion will develop a broader spectrum of damage across the structural system.

Ideally, the framework would be extended to be multi-hazard to capture the resilience of the structure to the entirety of an extreme event (i.e. blast or impact followed by fire at the location of damage). In a previous study, the authors have examined the consequences of fire that follows an initial extreme event that results in local damage (Quiel and Marjanishvili 2012), and the incorporation of fire in the framework would allow users to leverage studies such as these to develop a holistic rather than hazard-dependent assessment of structural resilience.

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