

Fragility of Built Urban Objects to Vicious Attacks: Assessment by Means of Limited Data on Abnormal Violent Actions

Egidijus Rytas Vaidogas

Vilnius Gediminas Technical University, Vilnius, Lithuania

Abstract

An assessment of fragility of objects built (constructed) in urban environment to deliberately imposed abnormal actions (loads) is considered. The actions under analysis are explosions, vehicular impacts and fires that can be imposed by acts of terrorism and sabotage as well as such highly random events as car crashes into structures due to unintentional roadway departures. The fragility is assessed by means of mathematical models known as fragility functions and developed for vulnerable building and transportation structures, protective barriers, and energy supply facilities. The result of fragility assessment is the probability of the damage that can be foreseen and modelled by means of mathematical models used for structural analysis. The case is studied where information on an abnormal action can be expressed in the form of a small-size statistical sample with components acquired in post-mortem investigations of attacks or unintentional accidents. The basic idea is an application of the statistical (bootstrap) resampling for the estimation the damage probability. The resampling procedure is applied to values of the fragility function that can be developed for the damage caused by the abnormal action in question. The values of the fragility function are estimated for components of the small-size sample of abnormal action values. The resampling of the fragility function values yields a conservative estimate of the damage probability expressed by the limit of a one-sided confidence interval. The estimate of the damage probability can be applied to making decisions concerning the level of resilience of vulnerable urban objects.

Keywords: abnormal action, damage, terrorism, small-size sample, inaccurate data, fragility, inverse analysis.

1. Introduction

Urban environment is a natural scene of such vicious attacks as acts of terrorism and sabotage as well as the primary site for taking counterterrorist measures (Fregonese & Laketa 2022). Terrorism is a phenomenon with many faces that are revealed by

classifications of violent incidents (Erickson, 1999; Purpura, 2019). For a long time, a variety of immovable objects built in urban environment has been the target of terrorist assaults called the physical incidents (Young, 2015). This study deals with physical terrorism threatening built urban objects. The acts of physical assaults on built objects are called the vicious attacks (VAs).

Built urban objects are sensitive to mechanical and thermal actions imposed in the course of VAs. Most structural objects built to date were conceptualized and detailed without taking into account the possibility of any VAs. The WTC twin towers completed in 1973 and destroyed in 2001 are a prime example of such objects. The decision concerning the protection of an existing or future structure against the hazard of AA contains at least four easily identifiable choices shown in Figure 1. Means of protection of previously unprotected structure are the same as or similar to ones that could be provided for a future potentially exposed object. However, independently of the status of exposed target, existing or future one, choice and detailing of protective structural elements will depend on prediction of foreseeable abnormal actions (AAs) imposed in the course of VAs.

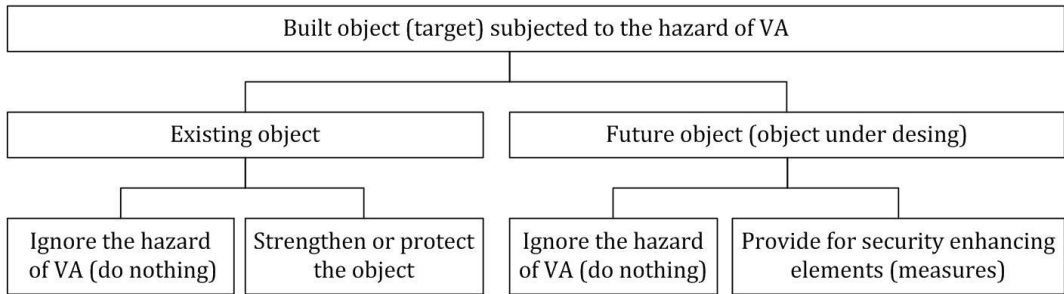


Figure 1. Four choices related to the decision concerning the protection of built objects against VAs

The present study is aimed at improving the prediction of damage to built urban objects by applying inaccurate data on AAs imposed during physical assaults. The main types of these assaults are malicious explosions and vehicle impacts. The gap of knowledge addressed in this study is how to estimate the likelihood of damage due AAs by means of inaccurate data on AAs generated in a relatively small number of VAs that happened in the past. The inaccurate data is modelled by subjective probability distributions that should be specified by the investigator of past incidents. A procedure that allows to propagate uncertainties expressed by inaccurate data to uncertainties related to the potential damage due to AAs is seen as the main added value of this study.

2. A Brief Review of Basic Equations Used for Assessing the Fragility of Built Objects Endangered by Vicious Attacks

From the standpoint of mathematical modelling, the damage to built urban objects (“targets” in what follows) caused by AAs imposed in the course VAs should be considered to be a random event. In what follows, this event will be denoted by the symbol Δ . The event Δ will be a consequence of a random event of AA imposition (event A) and the latter event in its turn will be triggered out by a random event of VA (event V). Thus we can write that the intersection probability of these three events is

$$\text{Prob}[\Delta \cap A \cap V] = \text{Prob}[\Delta/A] \text{Prob}[A/V] \text{Prob}[V] \quad (1)$$

An estimation of the probability $\text{Prob}[V]$ and circumstances of the event V are generally speaking a problem of security analysis (Osterburg & Ward, 2010). In other words it lies outside the traditional field of civil engineering and architecture. This probability depends on the type of the event V , history of occurrences of V , current political context. Thus the estimation of $\text{Prob}[V]$ will not be considered here. The product $\text{Prob}[\Delta/A] \text{Prob}[A]$ contains two factors. The first is related mainly to the structural engineering and the second should reflect knowledge on the physical phenomena occurring as the random event A (blast, impact by deformable body, temperature and thermal radiation resulting from an arsonist fire). In brief, the first probability $\text{Prob}[\Delta/A]$ lies on the structural side and the second probability $\text{Prob}[A]$ is related to predicting AAs.

Adding the additional factor $\text{Prob}[V]$ to the product $\text{Prob}[\Delta/A] \text{Prob}[A]$ supplements the engineering core of the problem with information related to security of potential targets (buildings, protective structures, energy lines, technological equipment of services used in urban environment). As we are interested in the engineering part of the problem, we can simplify it by assuming that the type of VA (event V) is known in advance and the event A will be triggered of by an occurrence of V . Then we have that

$$\text{Prob}[\Delta \cap A] = \text{Prob}[\Delta/A] \text{Prob}[A] \quad (2)$$

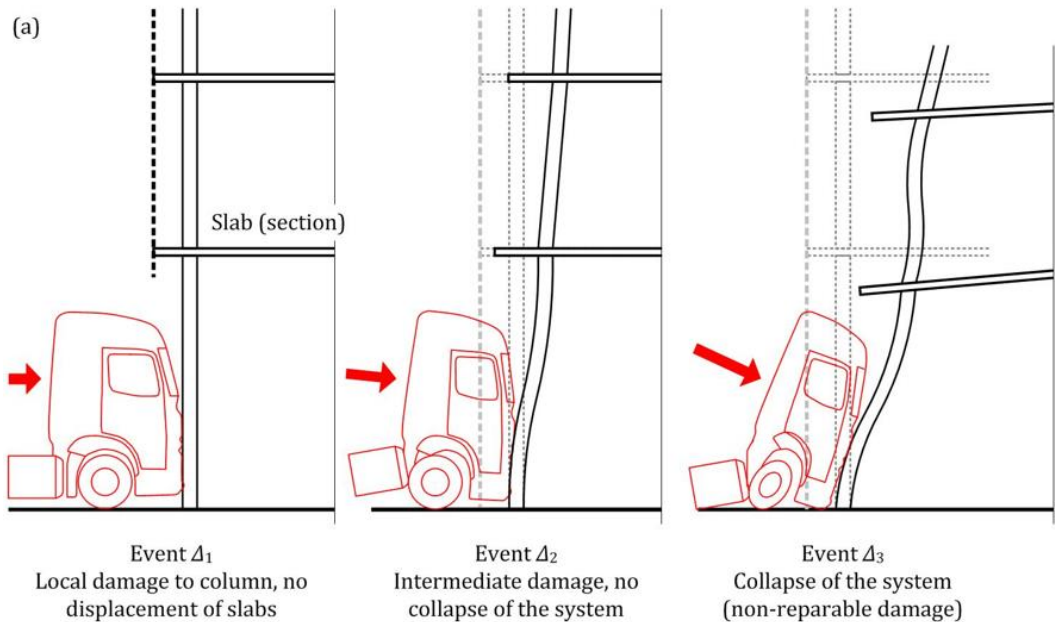
An assessment of fragility of the targets to a given AA presumes occurrence of the event A and exposure of a target to this event. In this context, the event A should be seen as a certain event with $\text{Prob}[A] = 1$. Then the problem reduces to an estimation of the conditional probability $\text{Prob}[\Delta/A]$. The above equation splits up the problem the fragility estimation into predicting vulnerability of a target to a given AA and assessing characteristics of this AA. These characteristics are usually expressed by a random vector $\mathbf{X} = (X_1, X_2, \dots, X_m)$, with a joint probability density function (pdf) $\psi(\mathbf{x})$

(Adam et al., 2018; Netherton & Stewart, 2009). With the vector \mathbf{X} , the probability $\text{Prob}[\Delta/A]$ is expressed as

$$\text{Prob}[\Delta/A] = \int_{\text{all } \mathbf{x}} \Phi(\mathbf{x})\psi(\mathbf{x}) d\mathbf{x} = E[\Phi(\mathbf{X})] \quad (3)$$

where $\Phi(\mathbf{x})$ is the fragility function developed for the damage event Δ and $E[\Phi(\mathbf{X})]$ is the expected value of the random function $\Phi(\mathbf{X})$. Eq. (3) arises from the field of seismic risk assessment and is now used in such fields as extreme wind risk analysis and nuclear power plant safety (Sundararajan, 1995).

In general, the event Δ present in Eqs. (1) to (3) can represent a very large number of damage states of target and AA in question. However, the estimation of the probability $\text{Prob}[\Delta/A]$ will be an affordable task if only a limited number of typical damage states, n_d , will be considered. Let these discrete damage states (random damage events) denote by Δ_d ($d = 1, 2, \dots, n_d$). An example of the events Δ_d that can be caused by a vehicular impact on a building is given in Figure 2a.



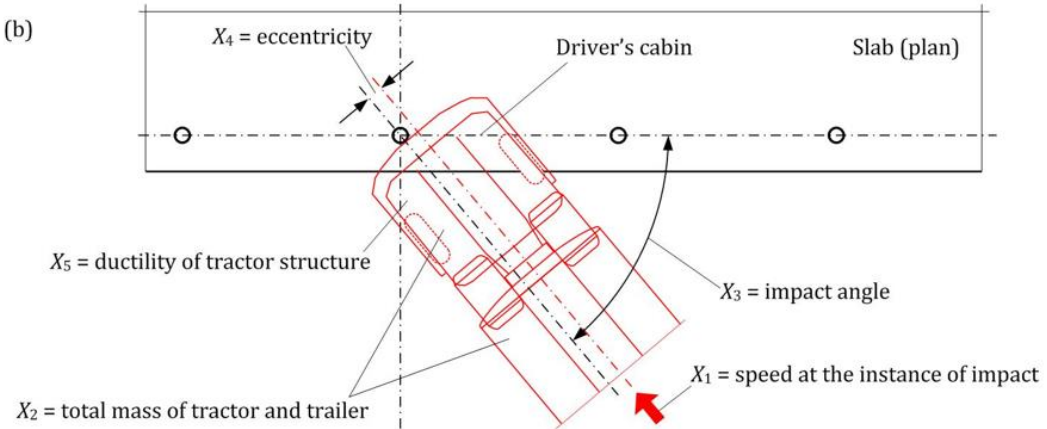


Figure 2. Illustration of the damage events Δ_t ($d = 1, 2, 3$) obtained by discretizing the continuous process of damage due to a vehicular impact (case (a)) and five characteristics X_j ($j = 1, 2, 5$) that describe AA caused by this impact (case (b))

The number of AA characteristics, m , is different for various situations of exposure of the target to AA. The number m will be equal to 1 in case of a simple reflection of a shock wave by dynamically insensitive structure (Bulson, 1997). The variable X_1 will represent the peak pressure in this case. If the target is a dynamically responding structure, information on blast loading will be represented by two characteristics: peak pressure X_1 and impulse (positive duration) X_2 . That is, m will be equal to 2. In more complex loading situations, the number m can be fairly high. An example of such situation is a vehicular impact on a ground floor column schematized in Figure 2b. One can easily identify at least five components of \mathbf{X} that can influence the interaction between impacting vehicle and structural system incorporating this column. The five characteristics of AA are illustrated in Figure 2b.

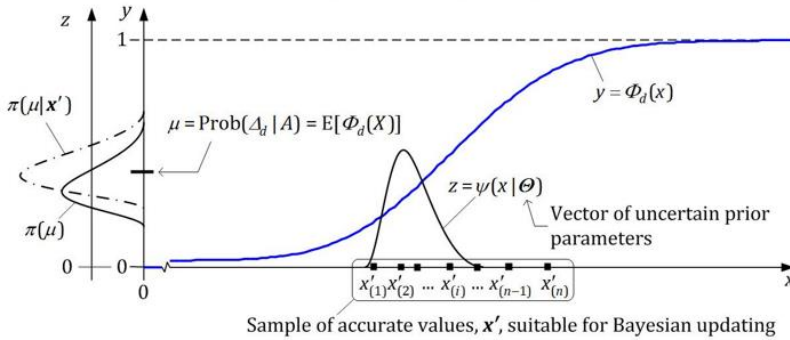
The interaction between AA and target can be highly complex. For instance, the spread of a shock wave in constrained environment may result in numerous reflections of the wave and complex process of loading. In addition, uncertainty related to AA as well as time-dependence of AA and response of the target to AA requires that this interaction should be viewed a short lasting random process. In this respect, the representation of AA by the random vector \mathbf{X} is a simplification used in many applications related to VAs without explicit justification. For the present, one can say that modeling AAs as short-lasting random processes is too complex to be attractive in practical sense.

For brevity and, as we hope, without loss generality, further consideration will be based on the assumption that AA under study can be characterized by a single random variable X with values x , that is, $m = 1$. In this case, Eq. (3) reduces to

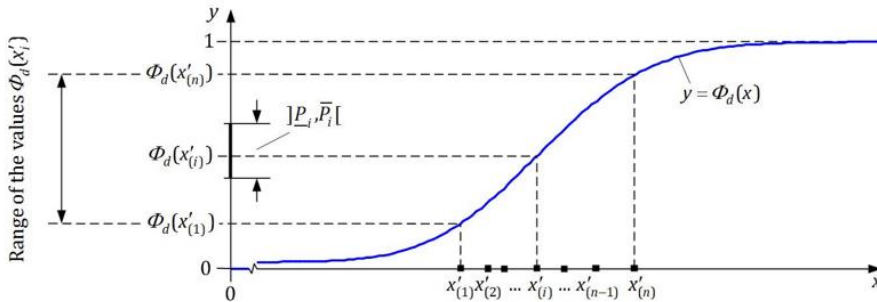
$$\text{Prob}(\Delta_d | A) = \int_{\text{all } x} \Phi_d(x) \psi(x) dx = E[\Phi_d(X)] \quad (4)$$

where $\Phi_d(x)$ is the fragility function developed for the discrete damage event Δ_d . This simplification allows to visualize the convolution of the functions $\Phi_d(x)$ and $\psi(x)$ that produces the probability $\text{Prob}(\Delta_d | A)$ (Figure 3a). Strictly speaking, the term “convolution” should be used only for a mathematical operation of two functions that produces a third function. This definition applies to the expression given by Eq. (4). However, this study uses this term in the broader sense to denote also a combination of the fragility function $\Phi_d(x)$ and information on values of AA that is not necessarily expressed by a single mathematical function.

(a) information on AA is expressed by a prior pdf $\pi(\mu)$ used for Bayesian updating with the sample x'



(b) information on AA is expressed by a small-size set of extracted from investigations of previous VAs



(c) information on AA is expressed by a small-size set of inaccurate data modelled by the pdfs $\psi_i(x)$

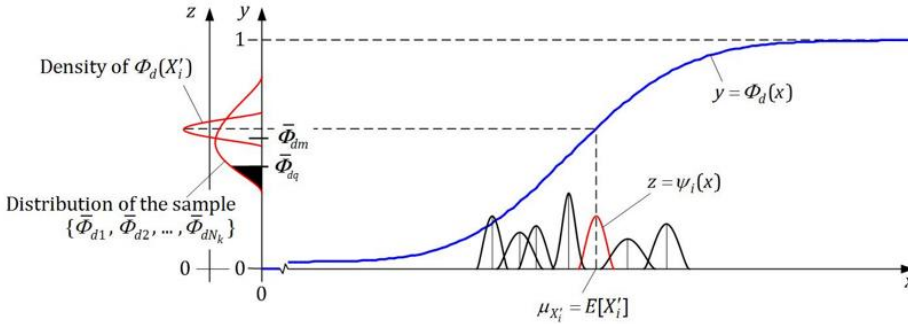


Figure 3. Illustration of the convolutions of the fragility function $\Phi_d(x)$ with three types of information on AA

3. Proposed Methodology for Prediction of Violent Actions With Limited and Inaccurate Information on their Occurrences

The present study considers the possibility to predict AA and the damage related to it by means of a small set of AA values extracted from investigations of previous VAs. The size of this set will be denoted by n and this number will be considered to be small in the sense of classical (Fisherian) statistics. Information that can be extracted from previous n incidents with AA under study can have three forms:

1. A set of values of the AA characteristic X expressed by $\mathbf{x}' = \{x'_1, x'_2, \dots, x'_n\}$. The ordered form of this set will be denoted by $\{x'_{(1)}, x'_{(2)}, \dots, x'_{(n)}\}$. The ordered set is illustrated in Figure 3ab. Elements of this set, x'_i , are fixed values, that is, there are no uncertainties in this data. In other words, values of X that took place in previous incidents are known accurately.
2. A set of probability distributions with the pdfs $\psi_i(x)$ (Figure 3c). The density $\psi_i(x)$ expresses uncertainty in applicability of an AA value related to the incident i . The value x'_i is not known accurately. Thus the information related to previous incidents is expressed by the set $\{X'_1, X'_2, \dots, X'_n\}$ and the corresponding set of pdfs $\Psi = \{\psi_1(x), \psi_2(x), \dots, \psi_n(x)\}$. As VAs of given type are usually not related to each other, components of this set, X'_i , can be independent random variables. The expectation of X'_i is denoted by $\mu_{X'_i}$ and shown in Figure 3c. In the field of the quantitative risk analysis (QRA), the data expressed by the probability distributions $\psi_i(x)$ is called the imprecise data (Kelly & Smith, 2009, 2011).
3. Mixture of the accurate values x'_i and inaccurate data modelled by the pdfs $\psi_i(x)$.

Information expressed by the set \mathbf{x}' can have different nature and can be used for the estimation of the damage probability $\text{Prob}(\Delta_d | A)$ in several ways. In the ideal case, the set \mathbf{x}' can be viewed as a representative statistical sample of an imaginary population of the past and future incidents in which the AA in question is generated. Then the damage probability can be estimated by two-sided or one-sided confidence intervals $]\bar{p}_i, \underline{p}_i[$ or $]0, \bar{p}_i[$ computed by means of a statistical (bootstrap) resampling of the values $\Phi(x'_1), \Phi(x'_2), \dots, \Phi(x'_n)$ (Vaidogas, 2005). Both $]\bar{p}_i, \underline{p}_i[$ and $\Phi(x'_{(i)})$ are illustrated in Figure 3b. Furthermore, the set \mathbf{x}' as a representative sample can be applied to Bayesian updating of the prior distribution specified to express epistemic uncertainty in the probability $\text{Prob}(\Delta_d | A)$ (Vaidogas & Juocevicius, 2009). In this case, the probability $\text{Prob}(\Delta_d | A)$ is interpreted as a population mean $\mu = \Phi_d(X)$, the prior distribution $\pi(\mu)$ is specified subjectively and the posterior distribution $\pi(\mu | \mathbf{x}')$ is estimated by a procedure of statistical resampling (Figure 3a).

The above approaches to the estimation of the damage probability $\text{Prob}(\Delta_d | A)$ with the data set \mathbf{x}' presume representativeness of \mathbf{x}' . In case of VAs, a formal proof of this data property is a problem that has not been addressed to date, to the best of our knowledge. We think that the accurate values x'_i can be obtained and a certain degree of representativeness achieved in an experimental investigation of AAs. However, this issue is beyond the scope of the present study.

Information on an AA of the type in question is inevitably accumulated with time. This process is highly sporadic due to an intermittent nature VAs. In addition, VAs are rare events even on the global scale, especially if a particular kind of AA is considered. The quality of knowledge on AAs is also influenced by varying sophistication of investigations into previous incidents. Not every investigation of physical incident results in an assessment of AA characteristics that can be expressed by the values x_i (or x in the one-dimensional case). Unfortunately, some guides for an investigation VAs and non-intentional incidents similar to VAs are official, nontechnical documents that do not explicitly require a backward estimation of an AA that caused damage at the scene of VA (DOJ, 2000; HSE, 2022). These documents regulate mainly the forensic investigation of incidents. On the other hand, forensic evidence can be useful for the backward engineering analysis (Sudoyo et al., 2008).

A general theoretical framework for determining values of AAs generated in past incidents is the methodology of inverse problems (Gallet et al., 2022; Spranghers et al., 2014; Yu et al., 2021; Zhou et al., 2021). However, values of x_i can be retrieved also by means of engineering methods rather than a rigorous scientific inverse analysis. For instance, peak pressure and impulse of a distant explosion can be estimated by looking at damage caused not only to the main target on the incident scene but also to such neighboring objects as lighting poles or façade glazing (Bulson, 1997). A comprehensive analysis of engineering (not forensic) methods developed

for retrieving values of AAs during investigations of incident scenes does not seem to be available. However, it can be said with confidence that estimates of AA characteristics retrieved during post-mortem investigations of VAs will hardly be accurate data expressed, for instance, by the fixed values x_i . Inevitable uncertainties in values of AAs will require to express these estimates as uncertain data and to use subjective probability distributions for modelling this uncertainty. Examples of modelling inaccurate data in QRA applications are provided by Siu and Kelly (1998) and Kelly and Smith (2009). In the format of the present study, results of investigation of n previous incidents are expressed by the set $\psi = \{\psi_1(x), \psi_2(x), \dots, \psi_n(x)\}$. Elements of this set, $\psi_i(x)$, quantify subjective uncertainty that is modeled by the random variables X'_i . A simple scheme for constructing the probability distribution of X'_i is shown in Figure 4. This scheme is based on the assumption that an investigation of the incident i will allow to obtain an approximate estimate (fixed likely value) of AA characteristic in question, x'_{iL} . Uncertainty in this value can be expressed by a subjective random variable ξ_i that will model the investigator's (analyst's) believe in the actual, albeit unknown value of the characteristic. The distribution of the imprecise value X'_i can be obtained by means of multiplicative scheme $X'_i = x'_{iL}\xi_i$ or additive scheme $X'_i = x'_{iL} + \xi_i$ depending on the investigator's preference. The type of the probability distribution of ξ_i will determine the distribution of X'_i and the pdf $\psi_i(x)$.

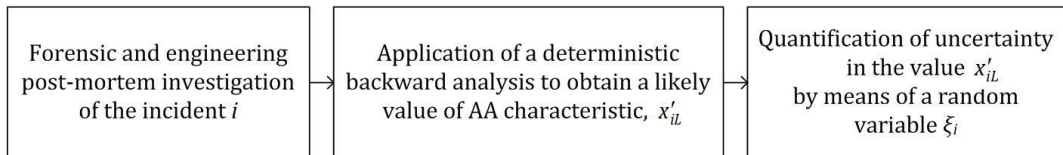


Figure 4. A scheme for specifying the subjective probability distributions of the inaccurate data X'_i on the basis of incident investigation results

The statistical quality the information expressed by the set $\psi = \{\psi_1(x), \psi_2(x), \dots, \psi_n(x)\}$ and its suitability for a rigorous estimation of the population mean $E[\Phi_d(X)]$ (damage probability $\text{Prob}(\Delta_d | A)$) is difficult to assess. The set ψ simply expresses information on the previous n incidents and this information can be a combination of objective and subjective knowledge on the AA under investigation. Processing uncertainties expressed by components of the set $\{X'_1, X'_2, \dots, X'_n\}$ through the fragility function $\Phi_d(X)$ will yield another set of random variables with the elements $\Phi_d(X'_i)$ (Figure 3c). The variables $\Phi_d(X'_i)$ can be used to compute a measure of the likelihood of the damage Δ_d , say, $L(\Delta_d | A)$. The term likelihood is used as a synonym of chance or possibility and not in the rigorous sense of the Bayesian updating. The likelihood $L(\Delta_d | A)$ will not necessarily coincide with the population mean $E[\Phi_d(X)]$. However,

this value can be used for making decisions concerning the vulnerability of targets under analysis to VAs. The value of the likelihood $L(\Delta_d | A)$ can be computed by means of the following algorithm of the stochastic simulation:

1. Generated the value $\{x'_{1k}, x'_{2k}, \dots, x'_{nk}\}$ of $\{X'_1, X'_2, \dots, X'_n\}$ from the probability distributions expressed by $\{\psi_1(x), \psi_2(x), \dots, \psi_n(x)\}$.
2. Compute the set of values of the fragility function, $\{\Phi_d(x'_{1k}), \Phi_d(x'_{2k}), \dots, \Phi_d(x'_{nk})\}$.
3. Compute the average $\bar{\Phi}_{dk} = n^{-1} \sum_{i=1}^n \Phi_d(x'_{ik})$.
4. Store the average $\bar{\Phi}_{dk}$.

A repetition of the above procedure N_k times will yield a simulated sample of averages of fragility function values, $\bar{\Phi}_d = \{\bar{\Phi}_{d1}, \bar{\Phi}_{d2}, \dots, \bar{\Phi}_{dN_k}\}$. A hypothetical distribution of this sample is shown in Figure 3c. The value of the likelihood $L(\Delta_d | A)$ suitable for decision making can be either the mean value $\bar{\Phi}_{dm}$ of the set $\bar{\Phi}_d$ or a conservative q -quantile $\bar{\Phi}_{dq}$ (with $q = 0.1$, say) of $\bar{\Phi}_d$. Both the mean value of $\bar{\Phi}_d$ denoted by $\bar{\Phi}_{dm}$ and the quantile are illustrated in Figure 3c. The values $\bar{\Phi}_{dm}$ and $\bar{\Phi}_{dq}$ are nothing more than a result of uncertainty propagation. The uncertainty expressed by the variables $\{X'_1, X'_2, \dots, X'_n\}$ is propagated to the likelihood measures $\bar{\Phi}_{dm}$ and $\bar{\Phi}_{dq}$. They must be compared to some tolerable values. This will require to answer the well-known question “how safe is safe enough”. It will be the task posed on urban community, what level of hazard posed by VAs can be tolerated.

4. Discussion

In line with the probabilistic procedure presented in this study, the assessment of fragility of built objects to AAs can be decomposed into two simpler sub-problems. The first sub-problem is a development of a fragility function for a damage event in question. The second sub-problem consists in collection and processing of information on the AA that can cause this damage and were encountered in past incidents. A solution of these two sub-problems for the case of VAs can be far from trivial.

A development of fragility functions is a problem of the structural reliability analysis (SRA). In a prevailing number of SRA applications, fragility functions have only one argument (earthquake loading, say) or two arguments (e.g., combined snow and earthquake loading) (Sundararajan, 1995; Lee & Rosowsky, 2006). However, an AA imposed on a built object can be characterized by three or more arguments (demand variables). An illustration of this case is the vehicle-ramming attack schematized in Figure 2b. A development of fragility functions having explicit form and more than two arguments can be an intricate task. To date, the only fragility function developed

for VAs seems to be a single-argument function of façade glass strength calculated for impulse of terrorists' explosions with a triangular time-pressure history (Stewart & Netherton, 2008).

The collection of the set of imprecise data on an AA under analysis can be another intricate task. It will require to group incidents with similar AAs and to extract information on characteristics of these AAs from incident investigation reports. This task cannot be solved by security specialists alone. Expertise in physical processes of AAs and special skills in modelling uncertainties related to possible values of these actions will be necessary. At the present time, methods for extracting information in the form of the aforementioned inaccurate data are still to be developed or improved in some special cases.

5. Conclusions

In this study, a procedure has been proposed for estimating the fragility of built urban objects to vicious physical attacks. The fragility is expressed as likelihood of the damage that can be caused by abnormal actions imposed in the course of such attacks. The procedure consists in propagating uncertainties related to abnormal actions generated in past incidents and expressing results of this propagation in terms of the damage likelihood. The propagation can be carried out by means of stochastic simulation and mathematical model of an endangered object known as the fragility function.

The main finding is that the damage likelihood can be assessed by generating values of inaccurate data and transforming these values into corresponding values of the fragility function. The measure of the likelihood can be average or conservative quantile of the transformed fragility function values. The inaccurate data can be retrieved from investigations of incidents that generated the abnormal action under analysis. The amount of this data will inevitably be limited because the number of incidents that generated a specific abnormal action is small event on the global scale. Inaccurate data should be considered as a prevailing type of information on abnormal actions, because a retrieval of precise, accurate data on such actions is hardly possible in case of an investigation of incidents that happened in the past. Estimates of the damage likelihood can be used for making decisions concerning protection of urban objects against vicious attacks.

An application of the proposed fragility estimation procedure will require further studies into development of multivariate fragility functions for characteristics of abnormal actions. Further work will be required for improving and refining extraction of processing of data on occurrences of abnormal actions in the past incidents.

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