# Probabilistic resilience assessment of infrastructure – a review



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*Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision – Caspeele, Taerwe & Frangopol (Eds)*
 *ISBN 978-1-138-62633-1*

# Probabilistic resilience assessment of infrastructure—a review

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ABSTRACT Resilience is quickly becoming a widespread method of assessing how a system, community or society responds to and recovers from a hazard. Hazards considered in this study include extreme weather and climate hazards such as extreme rainfall, flooding etc. Once 'rare' extreme weather events are now becoming increasingly frequent due to climate change, bringing with them the potential to cause significant disruption to infrastructure networks.

A quantitative analysis incorporating probabilistic fragility curves is presented here to assess vulnerable locations. This methodology may be expanded to determine resilience of an entire network or system. The capacity of the system to cope with any hazard may then be fully understood allowing recommendations to be made from both a global system perspective as well as at a local element level.

## 1 INTRODUCTION

### 1.1 *What is resilience?*

Resilience is typically defined as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of function and structure (Holling, 1973; Waller, 2001; Bruneau *et al.*, 2003; Croope & McNeil, 2011; RESILENS consortium, 2016). This could be in response to a climate hazard (e.g. flooding, hurricane), natural hazard (e.g. earthquake), or a man-made hazard such as a cyber-attack or terrorism. Once 'rare' extreme weather events are now becoming increasingly frequent due to climate change, bringing with them potential to cause significant disruption to infrastructure networks. The aim of this study is to develop a methodology to determine resilience of infrastructure components, elements and structures to climate change and extreme weather change events, with the ability to expand the methodology to a wider system or network.

### 1.2 *The need for resilient infrastructure*

Climate studies have demonstrated that extreme climate events are now becoming increasingly more frequent due to climate change effects, resulting in a need for our infrastructure to become more resilient (Hughes & Healy, 2014; Carey *et al.*, 2017). That is, a requirement for physical structures to withstand higher loading more frequently, for our emergency response organisations to react quickly, and for systems to resume normal operations quickly following a hazard/extreme event.

(Godschalk, 2003), focusing on cities, describes the importance of resilience as twofold:

– Firstly, because the vulnerability of technological and social systems cannot be predicted completely, resilience – the ability to accommodate change gracefully and without catastrophic failure – is critical in times of disaster. If we knew exactly when, where, and how disasters would occur in the future, we could engineer our systems to resist them. Since hazard planners must cope with uncertainty, it is necessary to design cities that can cope effectively with contingencies.
– Secondly, people and property should fare better in resilient cities struck by disasters than in less flexible and adaptive places faced with uncommon stress. In resilient cities, fewer buildings should collapse, fewer power outages should occur, fewer households and businesses should be put at risk, fewer deaths and injuries should occur and fewer communications and coordination breakdowns should take place.

It is therefore important that we can measure infrastructure resilience so we can better predict how infrastructure will respond to a hazardous event and we can better prepare for these events.

## 2 REVIEW OF RESILIENCE LITERATURE

### 2.1 *Definition of resilience*

Multiple definitions for resilience exist in published literature, however, the description typically centres on the ability of a system to recover and return to normal function following a hazard within a reasonable time. The concept of resilience originated in the fields of psychology and psychiatry in the 1940's (Waller, 2001; Johnson & Wiechelt, 2004), and has been used widely in the areas of environmental research, physics and sociology (Holling, 1973; van der Leeuw & Aschan-Leygonie, 2000). Resilience is frequently used to describe the ability of a community to respond and adapt following a hazard. It is only recently that this term has been applied to infrastructure and more specifically, transport infrastructure. The following is a selection of definitions of resilience:

– (Holling, 1973) working in the field of ecology describes resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables"
– (Wildavsky, 1988) refers to resilience as "the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back"
– In a study on community resilience to seismic events, (Bruneau *et al.*, 2003) defined resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes."
– In relation to disaster response workers, the following definition is given for resilience: "Resilience describes an active process of self-righting, learned resourcefulness and growth – the ability to function psychologically at a level far greater than expected given the individual's capabilities and previous experiences." (Paton, Smith & Violanti, 2000)
– In relation to transport infrastructure, (Croope & McNeil, 2011), introduced the concept of resilience as "the ability of a system to withstand or respond to changes". System resilience is also described as "the system's ability to provide and maintain an acceptable level of service when normal operations are challenged".
– With respect to infrastructure: "given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels", (Vugrin *et al.*, 2010).

Although these definitions all have slightly different approaches, the fundamental concept remains; the ability of a system to cope with a hazard and respond in an efficient manner. In a widely cited publication, (Bruneau *et al.*, 2003), community seismic resilience was studied and a number of new concepts were presented. They introduced the "four Rs", which have been widely applied to both physical and social systems, as:

i. Robustness refers to the strength or the ability of elements or systems to withstand a given level of stress or demand without suffering degradation or loss of function.
ii. Redundancy refers to the availability of substitutable elements or systems that can be activated when disruptions occur.
iii. Resourcefulness is the capacity to mobilise and apply material and human resources to achieve goals in the event of disruptions.
iv. Rapidity of response is the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

The four dimensions of resilience – TOSE – which relate resilience to all aspects of society were also introduced:

i. Technical: the response and performance of the physical systems when subjected to the hazard.
ii. Organisational: The capacity and ability of agencies/organisations to respond to emergencies and carry out critical functions.
iii. Social: The capacity to reduce the negative societal consequences of loss of critical services in the aftermath of catastrophic events.
iv. Economic: The ability to reduce the direct and indirect economic losses resulting from catastrophic events.

It is important to note the difference between the 'means' and the 'ends' of the properties of resilience. Resourcefulness and redundancy are the 'means' which allow the 'ends', robustness and rapidity of response, to be accomplished.

A number of definitions for resilience consider the resilience life cycle; that is before, during and after a hazard. (Bruneau *et al.*, 2003) describes resilience as the "ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)".

Consider both the TOSE dimensions and "four Rs" of resilience including restoration time, a multi-criteria optimisation process for resilience was developed in a qualitative approach (Bocchini, Paulo & Frangpol, 2011). Resilience itself is maximised, while costs and time taken to complete recovery are minimised.

### 2.2 *Relationships between resilience and other parameters*

A number of authors have also established relationships between resilience and other parameters such as vulnerability and sustainability. (Dong & Frangopol, 2016a; Bocchini *et al.*, 2014) developed a relationship between the complementary aspects of resilience and sustainability for civil infrastructure. Assessing both aspects would provide a complete assessment of the condition of the infrastructure.

(Lounis, 2013) has also published in the area of resilience and sustainability considering environmental impacts, user costs and life cycle costs.

In a qualitative study, the Argonne National Laboratory developed a resilience index considering vulnerability to allow comparison of facilities with one another (Fisher *et al.*, 2010). Based on the 4 'Rs', a comprehensive data collection system was developed with a weighting system so that the resilience index of individual facilities could be calculated. These can then be compared, allowing infrastructure managers to make better investment decisions.

### 2.3 *Interdependencies*

Interdependencies describe how systems or networks interact with and depend on one another. Although interdependencies are required for systems to function normally, they also bring vulnerabilities and increased risk of multiple failures. For example, a power network failure could cause knock-on failures in telecommunications, finance and energy sectors amongst others.

Infrastructure interdependencies have been considered through the use of Inoperability Input-Output Models (IIM) (Lian & Haimes, 2006; Jonkeren & Giannopoulos, 2014) and other interdependency measures (Guidotti *et al.*, 2016; Setola, De Porcellinis & Sforna, 2009).

### 2.4 *Probabilistic resilience assessment*

Probabilistic approaches have been adopted for several studies on resilience. A probabilistic approach to lifetime assessment of seismic resilience of concrete structures exposed to chloride-induced corrosion has been presented (Biondini, Camnasio & Titi, 2015). The proposed methodology found that the effects of corrosion may reduce system functionality over time, and consequently, make the seismic resilience dependent on the time of event occurrence.

Climate change and environmental impacts were considered by Dong and Frangopol in two papers (Dong & Frangopol, 2016b, 2016a). The resilience of bridges and buildings is assessed based on the probabilistic risk of hazardous events occurring.

(Chang & Shinozuka, 2004) enable resilience to be expressed more succinctly whilst retaining its multidimensional nature and also introducing a probabilistic context. They define resilience as the probability of meeting both robustness ($r^*$) and rapidity ($t^*$) standards in event $i$.

$$\Pr(A|i) = \Pr(r_0 < r* \; and \; t_1 < t*) \tag{1}$$

The term $R^*$ is also introduced as the Reliability Goal, which represents the minimum acceptable probability of meeting the standards in a given event. Thus, ideally $Pr(A|i) \geq R^*$ for any event $i$. The use of the new methodology as well as the reliability goal $R^*$ were demonstrated in a case study of the Memphis, Tennessee, water delivery system. Each of the four dimensions of resilience (TOSE – technical, organisation, social and economic) are measured pre- and post-earthquake simulation and a reliability goal is set. A variety of scenarios (with/without retrofitting) can be assessed against the goal to determine if additional improvements to resilience in the community are necessary.

A quantitative method incorporating probabilistic fragility curves to determine infrastructure resilience is presented in this study and the methodology will be outlined in the following section.

## 3 QUANTITATIVE RESILIANCE ASSESSMENT

### 3.1 *Resilience in terms of quality*

A concept introduced by (Bruneau *et al.*, 2003), is the idea of resilience as a quality measurement $Q(t)$ varying with time. This was also used and referred to as resilience index by (Nogal *et al.*, 2017). More specifically, system performance can range from 0% for no service to 100% at full service. For example, a system may be operating at 100% at time $t_0$, however, post-hazard at time $t_1$, this may be reduced to 50%. Over time, full service may be restored and if the system is completely repaired, 100% may again be achieved. Loss of resilience, $R$, or expected degradation in quality, is defined according to Equation 1 (Bruneau *et al.*, 2003; Bruneau & Reinhorn, 2007):

$$R = \int_{t_0}^{t_1} [100 - Q(t)] dt \tag{2}$$

The quality measurement, $Q(t)$ represents capacity or functionality of a system and may be expressed as follows (Bruneau & Reinhorn, 2007):

$$Q(t) = 100 - [L \cdot F \cdot \alpha_R] \tag{3}$$

$$Q(t) = 1 - [L(t_{0E}) \cdot f_{rec}(t, t_{0E}, T_{RE}) \cdot \alpha_R] \tag{4}$$

where $L = L(t_{0E})$ is the magnitude of loss function defined in Section 3.1.1, $F = f(t, t_{0E}, T_{RE})$ represents the recovery function after the time of event occurrence $t_{0E,}$ described further in Section 3.1.2, where $T_{RE}$ is the recovery period, and $\alpha_R$ is the functionality recovery factor ($\alpha_R = 1$ for full capacity replacement, $\alpha_R > 1$ if increased capacity is required, or $\alpha_R < 1$ if less than full capacity replacement is required).

All of the above variables in Eq. 3 vary between zero and one except where specified for $\alpha_R$.

#### 3.1.1 *The loss function, $L(t_{0E})$*

The loss function $L(t_{0E})$ is measured as the ratio of the actual loss $L_{LS}(t_{0E})$ (monetary, physical, technological and informational) at an expected performance limit state ($LS$) with respect to the cost of maintaining the full performance measure ($FP$) expressed in the same units as the loss, expressed as:

$$L(t_{0E}) = [L_{LS}(t_{0E})/FP] \cdot P_{LS}(R_{res} \geq LS) \tag{5}$$

where $P_{LS}(R_{res} \geq LS)$ is the probability that the system response $R_{res}$ will exceed the performance limit state, $LS$. This probability function is also known as

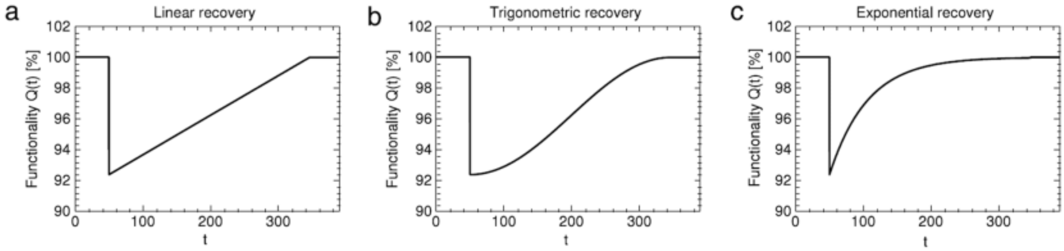


Figure 1. Recovery functions for (a) average prepared community, (b) not well prepared community, (c) well prepared community (Cimellaro, Reinhorn & Bruneau, 2010).

the fragility function, which is discussed in detail in Section 0.

As described by (Solomos & Caverzan, 2014), losses may be subdivided into direct ($L_D$) and indirect losses ($L_I$). Direct losses are those that occur instantaneously during the event, whilst indirect ones also have a temporal dependence. These losses may be further subdivided into economic losses ($L_{DE}$, $L_{IE}$) and casualties ($L_{DC}$, $L_{IC}$). Further detail on how to define and describe these losses is discussed in (Cimellaro, Reinhorn & Bruneau, 2010; Solomos & Caverzan, 2014).

#### 3.1.2 *The recovery function, F*

The recovery $F$ may also be described by a function $f_{rec}$ which is dependent on recovery time $T_{RE}$. In this work, we have considered three options for the recovery function which can be chosen depending on the system and society preparedness response (Solomos & Caverzan, 2014). These are linear, exponential and trigonometric as shown in Figure 1 and defined as follows:

Linear:

$$f_{rec}(t) = \alpha\left(\frac{t-t_{0E}}{T_{RE}}\right) + b \tag{6}$$

Trigonometric:

$$f_{rec}(t) = \frac{\alpha}{2}\{1+\cos[\pi b(t-t_{0E})/T_{RE}]\} \tag{7}$$

Exponential:

$$f_{rec}(t) = \alpha e^{\left[\frac{-b(t-t_{0E})}{T_{RE}}\right]} \tag{8}$$

where $\alpha$, $b$, are constant values that are calculated using curve fitting to available data sources and $t_{0E}$ and $T_{RE}$ are the time of event occurrence and recovery time respectively as described earlier. The type of function to be used is dependent on the information available about the system. If there is no information available regarding the preparedness, resources available and societal response, then the linear recovery function may be used (Eq. 6).

The trigonometric function may be used when there are limited resources or there is a lack of organisational preparedness (Eq. 7). The exponential recovery function can be used when the societal response is driven by an initial flow of resources but then the rapidity of recovery decreases as the process nears its end (Eq. 8) (Cimellaro, Reinhorn & Bruneau, 2010; Solomos & Caverzan, 2014).

Relationships between resilience and functionality, functionality and loss, and also between loss and fragility have now been established, allowing a probabilistic approach to be included when calculating component or system resilience.

### 3.2 *Functionality and fragility curves*

As seen in Eq. 4, fragility is used to describe the probability that system response will exceed the performance limit state (Bruneau & Reinhorn, 2007; D'Ayala *et al.*, 2014; Solomos & Caverzan, 2014; Barberis *et al.*, 2015; Ní Choine, O'Connor & Padgett, 2015; Guidotti *et al.*, 2016; Nogal *et al.*, 2017). Fragility curves are essentially cumulative distribution functions indicating probability of limit state exceedance of a structure for a given hazard intensity measure (Guidotti *et al.*, 2016), and usually "take the form of lognormal cumulative distribution functions, having a median value $\theta$ and logarithmic standard deviation, $\beta$" (Porter, Hamburger & Kennedy, 2007).

The European Commission's "Review on resilience in literature and standards for critical built-infrastructure" (Solomos & Caverzan, 2014) builds on fragility curves first presented in (Bruneau & Reinhorn, 2007) in relation to earthquake resilience, and develops them further. Fragility curves may be defined as follows (Barron-Corvera, 2000; Reinhorn, Barron-Corvera & Ayala, 2001; Bruneau & Reinhorn, 2007):

$$Fragility = F_Y = P_{LS}\{R_{res} \geq LS|I\} \tag{9}$$

where $R_{res}$ is the response parameter (damage, deformation, displacement, force, velocity, acceleration etc.), $LS$ is the limit state response parameter linked to the damage, and $I$ is the intensity of the event.

Following on from this, fragility curves for the system may be constructed and system functionality over time may be assessed (Solomos & Caverzan, 2014). Functionality curves describe system performance or

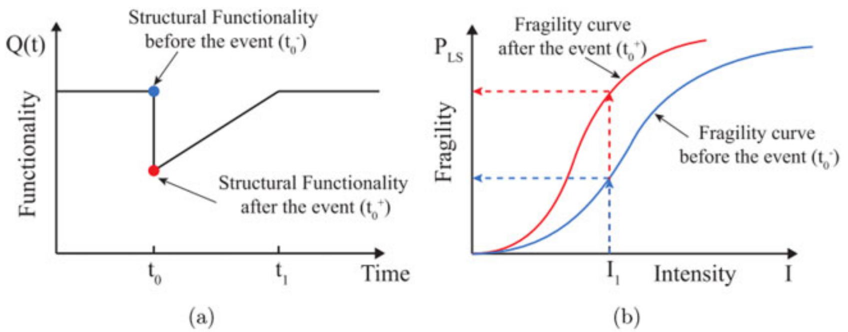


Figure 2. Effects of an event with intensity $I_1$ on the fragility curve: (a) functionality, (b) fragility curves (Solomos & Caverzan, 2014).

quality, $Q(t)$ (as described in Eq. 4), before, during and after a hazardous event.

The influence of retrofitting and resourcefulness can also be demonstrated by functionality curves (Solomos & Caverzan, 2014). In Figure 2(a), the functionality over time is presented. The structure remains undamaged up to time $t_0$ when an event of intensity $I_1$ occurs. Until that time, the fragility of the structure is represented by the blue curve (furthest right) in Figure 2(b). Due to the event, the system's fragility is increased, and is now represented by the red line (furthest left) in Figure 2(b). Therefore, if another event of intensity $I_1$ occurs, the fragility, or probability of damage to the structure is higher than for the undamaged structure.

### 3.3 *Developing fragility curves numerically*

As stated previously, fragility curves incorporate probabilistic assessment of individual elements as they represent the probability that the response of a structure exceeds a given threshold (of damage) for an event of specific intensity. The general expression for fragility (or probability of failure $P_{failure}$) is as follows:

$$P_{failure} = P\big((Demand > Capacity)|I\big) \qquad (10)$$

where $I$ is the hazard intensity measure. This may also be extended to a network or system resilience assessment by combining fragility curves as discussed later. The following section demonstrates how to construct fragility cures which contribute to the resilience calculations.

#### 3.3.1 *Fragility curve development*

Fragility curves for an infrastructure asset can be derived from a number of methods including field data, analytical methods or expert opinion. Ideally, field data on the component or element of interest at varying levels of demand would be available (Porter, Hamburger & Kennedy, 2007). However, field data can be expensive and difficult to obtain and so it will often be unavailable. In this case, fragility curves may be developed from alternative sources such as using expert opinion or numerical analysis (Porter, Hamburger & Kennedy, 2007; Jaiswal, Wald & D'Ayala, 2011). The typical methodology for developing fragility curves numerically is described briefly here (Ní Choine, 2013; D'Ayala *et al.*, 2015):

1. Select hazard or loading type and generate a number of loading values within an expected range at the location of interest.
2. Develop a group of stochastic capacity models representing the response at various points along the service life of the infrastructure element considering various levels of deterioration. This is done by sampling on the probability distributions of uncertain structural parameters such as concrete strength, steel strength, foundation stiffness etc. Some parameters are assumed to deteriorate with time whilst others are assumed constant over the service life of the infrastructure. The loading models generated in Step 1 are paired randomly to structural models in order to obtain a probabilistic distribution of the structural response over the service life of the component (Shinozuka *et al.*, 2003; Ní Choine, 2013).
3. Generate probabilistic demand model.
4. Formulate time dependent fragility curves based on component damage states, which correspond to a discrete level of damage. The probability that a component will be in damage state *i* at a particular level of demand *d* is then calculated. These are typically based on experimental results or expert opinion based on observed damage during past hazards. An example cumulative distribution fragility function for a particular damage state is shown in Figure 3(a) and the calculation of the probability that a component will be in damage state "*i*" at a particular level of hazard intensity or demand, "*d*" is shown in Figure 3(b). The lower, more shallow curve in Figure 3(b) demonstrates the probability that the system will be in a higher damage state "$i + 1$" following the hazard.

The first step is to establish the type of hazard or loading to be assessed, and generate a number of loading values within an expected range at the location

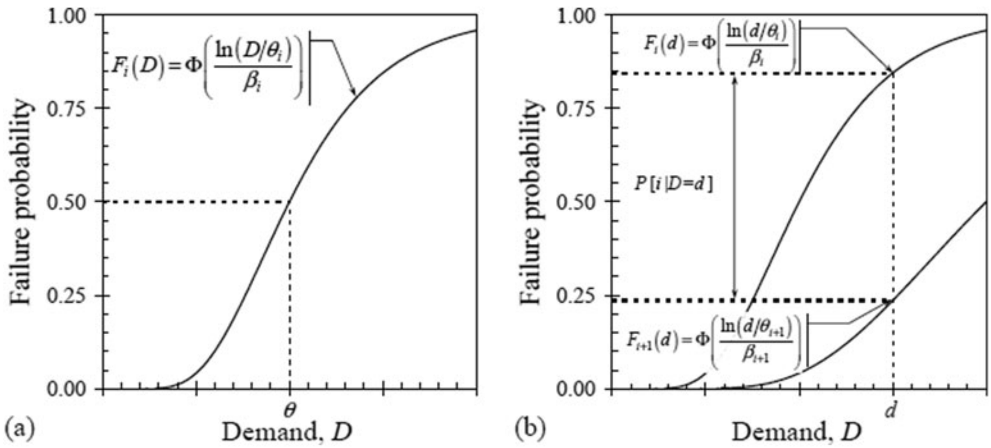


Figure 3. (a) Example fragility function, and (b) evaluating individual discrete damage state probabilities (Porter, Hamburger & Kennedy, 2007).

of interest. A series of finite element models of the infrastructure element can then be developed, pairing the loading models randomly to each structural model. The maximum responses of the components thought to contribute to the vulnerability of the infrastructure are recorded. The pristine response models are then modified to account for deterioration and the process is repeated at various points along the service life of the structure.

Probabilistic loading demand models are established for the component at each of the discrete points in time considered in the analysis. This provides a probabilistic model for each of the component demands for a given loading quantity. Probabilistic capacity models are also developed for each of the component limit states based on experimental results or expert opinion based on observed damage during past hazards. Similar to the demand models, the capacity models are developed at each service life point considered in the analysis. The lognormal distribution is typically used here to model demand and capacity as it fits a variety of component failure data well. It is a non-negative distribution which can also fit normally distributed data if required (Porter, Hamburger & Kennedy, 2007). If the demand and capacity are assumed to be independent variables, lognormally distributed at each point in time along the infrastructure's service life (Cornell *et al.*, 2002; Ghosh & Padgett, 2010, 2012), then based on the first order reliability method (FORM) solution for lognormal variables, the time dependent component fragility can be expressed as (Melchers, 1999):

$$P\left(\frac{Demand(t)}{Capacity\ (t)} > 1.0|I\right) = \Phi\left(\frac{ln\frac{S_D(t)}{S_C(t)}}{\sqrt{\beta_{D|I}^2(t)+\beta_c^2(t)}}\right) \quad (11)$$

where $S_D(t)$ and $\beta_{D|I}(t)$ are the time dependent median and dispersion of the demand model, $S_c(t)$ and $\beta_c(t)$ are the time dependent median and dispersion of the lognormally distributed component capacity and $\Phi$ is the standard normal cumulative distribution function.

For cases where the loading and capacity variables cannot be appropriately modelled by lognormal distributions, alternative reliability analysis protocols should be followed. A simulation procedure should be followed whereby the intensity measure (or hazard model) is varied over time, and the associated fragility (or failure probability) is calculated, e.g. using FORM, SORM (second order reliability method) or simulation (Connolly & O'Connor, 2017).

3.3.2 *Calculating resilience from fragility curves*

In order to determine system or network resilience, functionality curves may be generated from fragility curves, and resilience may be calculated from this. As demonstrated in Figure 2, functionality curves may be used to describe system or network functionality or capacity before, during and after a hazardous event. If fragility is already determined, functionality may then be calculated incorporating losses using Eq. 3. Loss of resilience, *R*, and thus resilience can subsequently be calculated using Eq. 2.

3.3.3 *Extension to overall system or network*

Failure of a component may have varying impact on the system as whole. Infrastructure components may be classified as primary or secondary depending on the impact of their failure on the overall damage to the system. If extensive or complete damage to a component would affect the stability of the infrastructural element, then it is considered a primary component. If damage to a component would not affect stability of the infrastructure, then it may be categorised as a secondary component. In this manner, the effect of failure of a component on the overall system may be determined.

Component fragility curves may be combined to generate fragility curves at a network level by summing the failure probabilities for each component in the network, provided component failures are independent mutually exclusive events. That is, the system analysis involves a logical consideration of the relevant potential failure events at a given limit state. So, the probability of the limit state being exceeded for the network is dependent on the sum of the probabilities of the limit states being exceeded for all mutually exclusive $k$ components in a series network.

$$P_{LS\ network} = \sum_k P_{LS\ component} \tag{12}$$

Note that the system probability value determined from Eq. 12 could theoretically be greater than 1.0, therefore, care should be taken in the logical consideration of the relevant components.

Once the network fragility curves are developed, network losses, functionality and resilience may then be calculated using Equations 2, 3 and 4. This calculation may also be extended to determine system functionality and resilience.

## 4 CONCLUSIONS AND RECOMMENDATIONS

In this paper, a review of existing methodology is presented for resilience assessment of a system, network, element or component adopting a quantitative approach. If cases where detailed structural data on system components is available, then a quantitative assessment employing fragility curves may be performed. This method may also be extended to system or network level, combining component fragilities to determine network resilience.

## ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 723254.

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