Building Failure Consequences

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Abstract

The consequences of structural failures (caused by an accidental action) typically come in several forms: for example fatalities, injuries, structural damage, damage to contents, loss of functionality and environmental damage. When considering structural failures these consequences are often divided into two categories, direct and indirect consequences. The type of consequences considered, and whether they are considered direct or indirect consequences, is dependent on the system boundaries. These should be defined clearly at the onset of any consequence analysis. Once the direct and indirect consequences are identified and quantified these values could be used to assess a structure's robustness, for example following the risk-based definition for this attribute suggested by Baker (2008).

The consequences of failure vary significantly from structure to structure, and may depend on a wide range of factors, including:

- Nature of the hazard;
- Properties of the structure;
- Use/occupancy;
- Location;
- Meteorological conditions;
- Time frame over which the consequences are assessed;
- The scope of consequences considered (in a socio-economic context).

As a result, the 'cost of failure' is a multi-dimensional and highly variable quantity, a fact that is reiterated throughout the literature on the topic (Soltani and Corotis, 1988; Kanda and Shah, 1997). These factors are discussed further in the following sections, and the various types of consequences arising from building failures are

examined. Additionally, this factsheet includes some suggested approaches for estimating some of these consequences. The methods and approaches reviewed herein are considered relevant to failure consequence analysis of general buildings and do not include buildings housing critical industrial facilities, such as nuclear power plants, chemical factories etc.

Keywords

Consequences; Failure cost; Failure analysis; Risk; Robustness

1 Introduction

The consequences of structural failures (caused by an accidental action) typically come in several forms: for example fatalities, injuries, structural damage, damage to contents, loss of functionality and environmental damage. When considering structural failures, these consequences are often divided into two categories, direct and indirect consequences.

- **Direct consequences *(C_{Dir})*** are those resulting from damage states of individual component(s) (Sørensen, Rizzuto et al., 2009). Generally, direct consequences are confined to the effects of immediate damage following the occurrence of a hazard and are related to the *vulnerability* of the structure.

- **Indirect consequences *(C_{Ind})*** are related to a loss of system functionality or failure, as a result of local failure, and are related to the *robustness* of the structure. Put simply, indirect consequences occur as a result of direct consequences.

Figure 1 illustrates the direct and indirect consequences in terms of the risk assessment framework adopted to analyse the robustness of a structure.

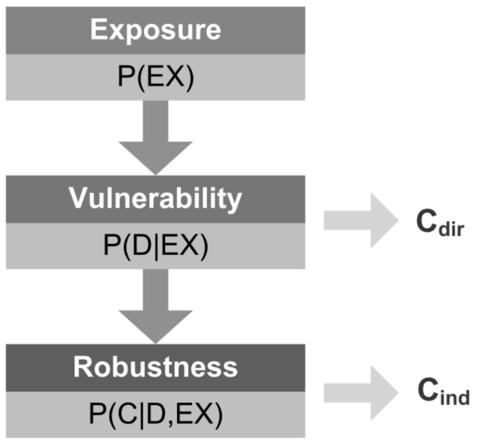

Figure 1: Relationship between robustness, vulnerability and consequences (based on JCSS, 2008)

Before undertaking a consequence analysis it is important to debate with stakeholders and clearly identify the system boundaries. In particular, the distinction between vulnerability and robustness should be stated (and therefore the distinctions between the direct and indirect consequences can be made). Consider the example of a bomb which detonates beside a supporting column, in the basement of a multi-storey building. It is likely that the column will be destroyed, resulting in the failure of the supported floor and, possibly, the subsequent collapse of the entire structure. The vulnerability may be associated with (i) the column failure, (ii) the failure of the supported floor or (iii) the collapse of the entire structure. Meanwhile, the robustness is a ‘knock-on’ effect of the vulnerability, and may be related to (i) the collapse of the supported floor, (ii) the collapse of the entire building or (iii) the building collapse and its effect on the surrounding environment. These must be identified clearly, as part of the system boundary definition, before the consequences can be quantified.

2 Factors affecting the consequences of failure

The consequences of failure vary significantly from structure to structure, and may depend on a range of factors; related to the hazard, the structure and the surrounding environment.

The **nature of the hazard** will considerably affect the consequences considered. It is evident that the greater the magnitude and duration of a hazard, the greater the consequences will be. But the type of hazard will also have an effect. Additionally, it is important to specify if a hazard poses an additional risk to humans (or animals) though exposure, inhalation or ingestion.

The **properties of the structure** will influence both the vulnerability and robustness of the building. The consequences will be sensitive to factors such as the materials used, building type, age, size, height, layout (including ease of evacuation), type of construction and quality of construction. The consequences of failure are also dependant on the **use or occupancy** of a building. As well as governing the number of people exposed to the hazard, and therefore the possible number of injuries or fatalities, this will influence the building contents and the quality of building services and finishes (e.g. ventilation, plumbing and electrical systems) present.

Buildings in rural areas, or close to a water source, may be more vulnerable to environmental consequences as pollutants may be more easily transported in open air/water. In contrast, the number of people exposed to pollutants in urban areas will be greatest, increasing the human consequences. Also, the availability of emergency services and accessibility to treatment for injuries will most likely be best in urban areas. Therefore, the proportion of fatalities may be lower in these locations. Consequently, an increased number of injuries may be observed in urban areas (due to the expected increased survival rate). Finally, when studying the cost of repair or reconstruction, remote locations may have higher costs due to increased labour and materials costs. In other words, the **location** of a building will have some bearing on the consequences arising from any given failure event. Hence, it is important to include location as a contributing factor in evaluating consequences.

Depending on the **time of day**, different building types may experience different occupancy levels (Figure 2). Places of work and education will experience high levels of occupancy during working hours. But at night these buildings may be almost empty. In contrast, residential buildings will reach peak occupancy at night, when the occupants are sleeping. Therefore, the potential for mass casualties is dependent on both the time of day the exposure occurs and the occupancy pattern for the structure. Further temporal variations may occur daily, weekly, monthly, seasonally etc. Additionally, the **time frame considered** (days/weeks/years) in the consequence analysis will affect the outcome of such an analysis. For example, in order to capture the influence of long-term effects (e.g. latent cancers) associated with nuclear accidents a longer period of time must be considered than would be the case for the collapse of an agricultural silo.

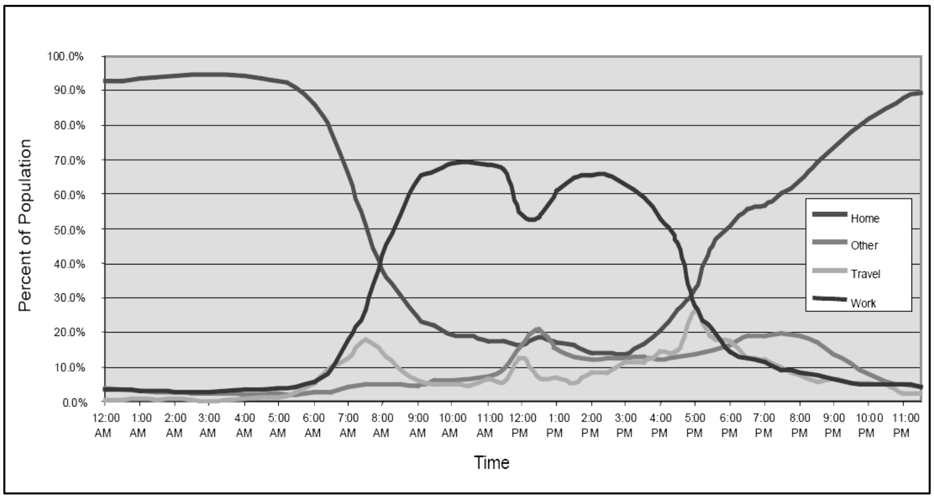

Figure 2: Activity patterns of working age, professional females during a normal work day (Coburn and Cohen, 2004)

Finally, the **meteorological conditions**, both during and after the failure event, may have some impact on the consequences. In particular air conditions (including wind direction, wind speed, terrain etc.) will influence the level of dispersion of any toxic pollutants, leading to an increase or decrease in the environmental consequences accordingly.

3 Treatment of consequences in the Eurocodes

The design of structures to resist accidental actions is dealt with in EN 1991-1-7 (CEN, 2006). This document classifies building structures according to their consequences of failure, which in turn determines the design criteria for achieving robustness. There are three possible classes listed:

CC1 **Low** consequence for loss of human life, *and* economic, social or environmental consequences are **small or negligible**

CC2 **Medium** consequence for loss of human life, *and* economic, social or environmental consequences are **considerable**

CC3 **High** consequence for loss of human life, *and* economic, social or environmental consequences are **very great**

The recommended procedures for achieving robustness are dependent on the assigned consequence class, with the complexity of the required procedure increasing as the consequences of failure increase. The consequences are assumed to be dependent on the building type, number of storeys and the floor area (see Table 1).

Consequence Class	**Example of categorisation of building type and occupancy**
1	Single occupancy houses not exceeding 4 storeys. Agricultural buildings. Buildings into which people rarely go, provided no part of the building is closer to another building, or area where people do go, than a distance of 1½ times the building height.
2a (lower risk group)	5 storey single occupancy houses. Hotels not exceeding 4 storeys. Flats, apartments and other residential buildings not exceeding 4 storeys. Offices not exceeding 4 storeys. Industrial buildings not exceeding 3 storeys. Retail buildings not exceeding 3 storeys, of less than 1000 m^2 floor area in each storey. Single storey educational buildings. All buildings not exceeding two storeys to which the public are admitted and which contain floor areas not exceeding 2000 m^2 at each storey.
2b (upper risk group)	Hotels, flats, apartments and other residential buildings greater than 4 storeys but not exceeding 15 storeys. Educational buildings greater than single storey but not exceeding 15 storeys. Retailing premises greater than 3 storeys but not exceeding 15 storeys. Hospitals not exceeding 3 storeys. Offices greater than 4 storeys but not exceeding 15 storeys. All buildings to which members of the public are admitted and which contain floor areas exceeding 2000 m^2 but not exceeding 5000 m^2 at each storey. Car parking not exceeding 6 storeys.

Table 1: Definition of consequence classes, from EN 1991-1-7 (CEN, 2006).

Consequence Class	Example of categorisation of building type and occupancy
3	All buildings defined above as Class 2 Lower and Upper Consequences Class that exceed the limits on area and number of storeys. All buildings to which members of the public are admitted in significant numbers. Stadia accommodating more than 5000 spectators. Buildings containing hazardous substances and/or processes.

Table 1 (cont.): Definition of consequence classes, from EN 1991-1-7 (CEN, 2006).

In Annex B of EN 1990 (CEN, 2002) these three consequence classes are used to determine the level of reliability to be achieved in design. For increasing severity of consequences, the target reliability increases, resulting in the design of stronger, more ductile structures.

4 Classification of Consequences

In order to study the individual consequences resulting from a building failure, they may be divided into three categories: economic, human and environmental consequences (Table 2).

	DIRECT CONSEQUENCES	INDIRECT CONSEQUENCES
Human	Injuries Fatalities	Injuries Fatalities Psychological Damage
Economic	Repair of initial damage Replacement/repair of contents	Replacement/repair of structure Replacement/repair of contents Loss of functionality/production Temporary relocation Clean up costs Rescue costs Regional economic effect Investigation/compensation Loss of reputation
Environmental	CO_2 Emissions Energy use Toxic releases Environmental Studies/Repair	CO_2 Emissions Energy use Toxic releases Environmental Studies/Repair

Table 2: Classification of Consequences

Difficulties may arise when trying to compare different types of consequences. For example, in order to compute an overall 'failure cost', one may wish to assign monetary values to the different consequences (fatalities, injuries, CO_2 emissions etc.), which could then be used as part of a cost-benefit analysis. But, this may not always be the most suitable approach, especially if the environmental or human consequences are significant. In this case, a multi-criteria analysis (DTLR, 2001) may be more appropriate.

Finally, it is important that a clear distinction is made between different consequences, possibly with different units of measurement. For example if the rescue costs (e.g. fire brigade, ambulance) are included in a consequence analysis, one should be careful not to include the costs associated with pre-hospital treatment in the injury cost term. This is fundamental to ensuring consequences are not omitted or double-counted.

5 Classification of Damage Severity

Damage to a structure will probably only be a small part of the total consequences, but the level of damage experienced/recorded is the root cause of both structural and non-structural consequences. Therefore, economic and other costs for the consequences can be estimated using the level of damage experienced. In order to achieve this, a consistent measure of the damage severity must be developed.

In the area of earthquake loss estimation, a large amount of research into estimating the consequences of earthquakes has been undertaken. A number of models exist which relate the level of structural damage observed to the consequences (Nathwani, Lind et al., 1997; Spence, So et al., 2008). These approaches could be applied to building failures caused by accidental actions, but it is important to be aware of the different properties of these actions.

In earthquake engineering, the various approaches to damage categorisation are based on a variety of intensity scales: the European Macroseismic Scale (EMS) (Coburn, Spence et al., 1992) being the most common scale in Europe. The EMS divides the level of damage into six grades (including grade D0 for no damage), and structures are assigned a damage grade according to the level of visible damage. This document also includes a list of visual indicators, for masonry and reinforced concrete buildings, to assist the grading process. This scale could be adopted for building failure resulting from exposures other than earthquakes. However, the visual damage indicators may require some revision before their application. This is due to the fact the visual indicators used are characteristic of earthquakes However, for failure of buildings following accidental actions a wider range of visual indicators would be necessary. For example, the proportion of the total horizontal area (including both floor and roof areas) that has collapsed may be a suitable indicator. Table 3 is based on the damage grades found in the EMS, which have been adapted to include a proposed classification system for damage resulting from accidental actions. In the case of the EMS classification, fully and partially collapsed buildings would be assigned grade D5 (grade D4 for collapse of an individual wall). This proposed classification recognises the importance of distinguishing between different degrees of partial collapse, when determining the consequences of accidental actions. Therefore, grade D5 accounts for fully (or almost fully) collapsed buildings, while partially collapsed buildings are assigned to the remaining categories.

Grade	Damage level	*Percentage of horizontal area collapsed*
D0	**No Damage**	*0%*
D1	**Negligible to slight damage** No structural damage, slight non-structural damage	*<1%*
D2	**Moderate damage** Slight structural damage, moderate non-structural damage	*1-10%*
D3	**Substantial to heavy damage** Moderate structural damage, heavy non-structural damage	*10-50%*
D4	**Very heavy damage** Heavy structural damage, very heavy non-structural damage	*50-80%*
D5	**Destruction** Very heavy structural damage	*80-100%*

Table 3: EMS damage grades with *proposed* classification system for damage resulting from accidental actions (adapted from Coburn, Spence et al., 1992)

6 Human Consequences

The human consequences (fatalities, injuries and psychological damage) of structural failures can be highly variable, with emphasis so far being given to the estimation of mean values.

6.1 Fatalities

Coburn, Spence et al. (1992) developed a model for predicting fatalities as a result of building collapse following earthquake. Although building collapses as a result of earthquakes may have some differences from those caused by accidental actions, this model offers a good starting point for predicting the number of fatalities as a result of an accident. For a class of building, *b*, the authors defined the number of people killed, K_s, as

$$Ks_b = D5_b * [M1_b * M2_b * M3_b(M4_b + M5_b)] \quad (1)$$

Where $D5_b$ is the total number of collapsed structures of building type *b*, and factors *M1* to *M5* are a range of modifiers. *M1* is defined as the number of people per building type *b*, reflecting the number of people exposed to the hazard. The modifier *M2* represents the percentage of people in the building at collapse. If detailed occupancy cycles (similar to that shown in Figure 2) are not available, average occupancy levels can be assumed for *M2*. Typical average daily occupancy levels for residential urban buildings, non-residential urban buildings and rural agricultural buildings are proposed as 65%, 40% and 45% respectively (Nathwani, Lind et al., 1997).

M3 accounts for the fact that only a portion of a building's occupants will be trapped by the collapse, while the remaining occupants will be able to escape or free themselves relatively easily from the rubble. For the failure of buildings due to accidental actions, the location at which the hazard occurs and the time taken for the building to reach its final collapse state will influence the portion of occupants collapsed. For damage levels *D4* and *D5*, a reasonable assumption is that all occupants in the storey at which the hazard occurs, *h*, or the storeys above will be trapped by the collapse. Therefore, for a building with *n* storeys (where the ground floor corresponds to $i=0$, and the roof to $i=n$) *M3* can be defined as

$$M3 = \frac{1}{n+1}\left(\sum_{i=h}^{n} A_{\%col,i} + \gamma \sum_{i=0}^{h-1} A_{\%col,i}\right) \qquad (2)$$

where $A_{\%col,i}$ is the percentage of the horizontal area that has collapsed at the i^{th} storey and γ is the percentage of people able to evacuate the building before collapse. When the time from the occurrence of the hazard to the building reaching its final damage state is relatively small (i.e. less than 30 sec), it is reasonable to apply the proposal by Coburn, Spence et al. (1992) that 50% of the occupants of the ground floor (of reasonable plan area) will be able to escape, but all other occupants will remain inside. Hence, Equation (2) can be rewritten as:

$$M3 = \frac{1}{n+1}\left(\sum_{i=h}^{n} A_{\%col,i} + \frac{h-0.5}{h}\sum_{i=0}^{h-1} A_{\%col,i}\right) \qquad (3)$$

M3 should be reviewed on a case-by-case basis, increasing or reducing the proportion of occupants who escape depending on the extent to which evacuation is impeded by any immediate damage. Also, structures with damage levels D1-D4 may result in lower numbers of fatalities, as occupants may escape being trapped by moving to a portion of the floor they are occupying which has not collapsed.

M4 signifies the number of people killed instantly by the collapse, as a percentage of *M3*. As different types of buildings will inflict injuries in different ways and to different degrees of severity, the building type should be considered when deciding on an appropriate value for this factor. Coburn et al. (1997) suggested that *M4* be taken as 0.2 and 0.4, for masonry and RC structures respectively. However, again this may require revision for failures resulting from accidental actions. Finally, *M5* is the post-collapse mortality factor and can be considered a measure of the effectiveness of rescue operations and medical activities. The authors proposed a range of values for *M5,* depending on the construction material the effectiveness of the emergency response. The values suggested range from 0.45-0.9 for masonry buildings, and 0.7-0.9 for RC buildings.

An alternative approach for estimating the number of fatalities following earthquake can be found in HAZUS (2003), which could also be adapted to building failure due to accidental actions.

Once the estimated number of fatalities is determined, one may need to quantify this consequence in monetary terms, in case an overall ‘failure cost’ is required. In implementing such an approach, the economic value of human life has to be considered. A wide range of approaches are available to estimate this value, including:

(i) *Willingness-to-pay (WTP) or willingness-to-accept (WTA) approaches*

Values based on these methods are usually taken from legal precedent, (e.g. Government compensation payable for death by accident). For example, after the collapse of the World Trade Centre Twin Towers, the Victim Compensation Fund (set up by the United States of America’s Federal Government) awarded an average compensation of over 2.08 million USD per fatality (Faber, Kübler et al., 2004).

(ii) *Value of a statistical life (VSL)*

The value of statistical life is equal to *Dx*, where *D* is the amount an individual is prepared to pay to reduce their fatality risk by 1^{-x}. Cited values for this term range from 200,000 USD to almost 30 million USD in 1997 prices (de Blaeij, Florax et al., 2003). In the UK, the HSE (2001) adopts a benchmark value of 1 million GBP (2001 price) for the value of preventing loss of a life, for use in a cost-benefit analysis.

(iii) *Money spent on government programmes per life saved*

The amount spent on government programmes per life saved ranges from 100,000 USD for steering column protection to 90 million USD for asbestos removal (Faber and Stewart, 2003).

(iv) *Insured Value*

For group life insurance policies, the payment received upon death is usually a multiple of the policyholder’s salary level. Whereas, for individual life insurance policies, the payment received is a specific coverage amount purchased by the policyholder and is usually related to the number of dependants and the individual’s profession among other factors (Coburn and Cohen, 2004). Additional lines of insurance coverage which may apply are workers compensation, accidental death and dismemberment (AD&D) and health insurance.

(v) *Earnings lost due to premature death*

A value of 450,000 USD is quoted by Faber and Stewart (2003) though this would depend on the context in which this value is calculated and could vary quite significantly due to a number of factors (e.g. age, profession, country).

(vi) *Life Quality Index (LQI)*

The Life Quality Index (LQI) is a more meaningful estimate of the economic value of human life, which reflects the quality of life in a society or group of individuals (Nathwani, Lind et al., 1997; Faber and Stewart, 2003; Lentz and Rackwitz, 2004). The LQI is derived from two social indicators: the life expectancy at birth, *e*, and the real gross domestic product (GDP) per person, *g*.

$$L = \frac{g^q}{q} e \qquad \text{where} \qquad q = \frac{w}{1-w} \tag{4}$$

where *w* is the average fraction of life expectancy spent at work (typically taken as 20%). This value has been optimised to determine an acceptable implied cost of saving a human life of ca. 2-3 million USD (Faber and Stewart, 2003).

Alternatively, human consequences can be considered separately to the overall failure cost, resulting in a multi-objective optimisation problem to achieve the optimum balance between robustness and risk/consequences.

6.2 Injuries

The costs related to injuries may be significantly higher than those for fatalities, and could include pre-hospital emergency treatment, emergency department services, hospital physician and surgeon services, visits to private physicians, rehabilitation costs and lost income. As there is no standard threshold at which victims may be classified as injured, and as some persons not requiring emergency treatment may seek private treatment or choose to self-medicate, the statistics for casualty numbers from past failure events are often inconsistent (Spence, 2007). This makes it very difficult to predict the number of injuries for a certain hazard scenario. The type/severity of injuries resulting from a structural failure may be more easily related to the hazard, the resulting level of damage and the properties of the structure occupied. A considerable amount of research has been undertaken to develop relationships between the level of damage to buildings following earthquakes and the injuries observed (Spence, 2007).

A wide range of injuries are associated with building collapse. An investigation into the injuries and fatalities following the Oklahoma City Bombing (Mallonee, Shariat et al., 1996) identified a variety of injuries as a result of the blast and the ensuing building collapse. Severe, potentially fatal or disabling soft tissue injuries were the most prevalent type of injury. Additionally, in decreasing order of occurrence, muscuskeletal injuries, head injuries, auditory damage, ocular injuries, thermal burns (mostly to the face and neck), internal organ injuries and respiratory problems were observed. Most of these injuries (excluding auditory damage and thermal burns) could be expected in most building failures, as a result of the large amounts of dust, falling debris and flying glass generated. The injuries sustained will also depend on the type of building occupied, with crushing of the spine often associated with collapse of concrete buildings.

A large amount of research into evaluating the consequences of illness has been undertaken in the medical profession. The World Health Organisation (WHO) *Guide to Identifying the Economic Consequences of Disease and Injury* (2009) provides a detailed review of the factors contributing to these consequences and of the techniques (e.g. 'cost-of-illness') used to evaluate the cost of the consequences. Additionally, the WHO CHOICE project has produced costs per hospital stay by hospital level, outpatient visits, and cost of outpatient visits, for the 14 WHO regions (available at www.who.int/choice). Information from the insurance industry can be used to estimate the level of compensation injured individuals may receive for pain and suffering. The Book of Quantum (PIAB, 2004) provides a list of the suggested compensation for a wide range of injuries, from loss of a tooth (€3,600-€5,700) to paralysis (up to €300,000). Finally, the loss of earnings for the individual should also be considered.

6.3 Psychological damage

The psychological damage experienced by a structure's owners/occupants, as well as the effect on victims (and relatives of victims), may also be considered. However, this is extremely difficult to quantify. It may be possible to relate the psychological damage to owners/occupants to the structures use, as proposed by Kanda and Shah (Kanda and Shah, 1997). The authors suggested that the psychological loss associated with damage to a private house may be as high as the cost of construction of that house, due to the significant grief associated with losing one's home. In comparison, the psychological loss associated with damage to a small shop or rented apartment is significantly less, but still greater than that for a hospital or nuclear power plant.

The psychological damage experienced by injured victims will depend on the extent of injury among other factors. Faizian, Schalcher et al. (2005) summarised the psychological damage as a result of earthquakes as fear, helplessness, distress, depression and suicides, and proposed that they may be related to the consequences of the earthquake (loss and damage). It is likely that similar psychological effects may be triggered by building collapse, caused by accidental actions. These factors are not normally included in a consequence assessment. However, psychological consequences can result in reduced efficiency in a region following a failure event, which should be recognised in a comprehensive consequence analysis, and could be extremely relevant in the case of catastrophic scenarios (though this is unlikely to be related to building failures as opposed to the failure of an industrial facility). These factors may be included in the injury cost term or dealt with separately. Finally, the psychological damage experienced by the relatives of any person killed or injured might, or might not, be included, depending on the scope of consequences considered.

7 Economic Consequences

The economic consequences of structural failure include tangible factors such as the cost of rebuilding (or repair), the cost of loss of functionality etc. However, in order to accurately compute the economic cost of failure, an attempt should be made to quantify intangible factors such as market price effects, loss of reputation etc.

7.1 Replacement/repair

The cost of replacement/repair for a structure can be divided into two categories: the cost of replacement/repair of structural components (structural cost) and the cost of replacement/repair of its contents (non-structural cost).

The structural cost will be dependent on the extent of damage, structure type, size etc. and can be estimated from the initial construction cost. This value should account for all building components, including piping, mechanical and electrical systems, building materials and built-in fixtures. The building replacement cost models used in HAZUS (2003) are based on industry-standard cost-estimation models and provide a good starting point for estimating this term. Table 4 provides a selection of the full replacement costs provided in HAZUS, for each occupancy class.

The non-structural cost will depend on the market price and nature of the contents, which should both be taken into account, as well as the extent of damage. This can be more difficult to quantify, requiring greater detail about the function of the structure. HAZUS simplifies the estimation of non-structural costs by assuming the non-structural cost is directly related to the structural cost. Table 4 lists the structural and non-structural costs for complete reconstruction of a range of building types (corresponding to EMS damage level D5).

7.2 Temporary relocation

For failure of residential structures, a significant number of residents may require temporary shelter until their homes are inhabitable again. Relocation costs will also be associated with the failure of office and retail buildings, but they will most likely be significantly lower. Additionally, some individuals may indirectly find their homes uninhabitable following the failure of another building (for example due to loss of water or power). This should also be considered in any comprehensive consequence analysis.

HAZUS Occupancy Class Description	Sub-category	Cost/ft^2 (cost/m^2) in USD	
		Structural	**Non-Structural**
Multi family dwelling – medium	5-9 units *apartments, 1-3 storeys, 8,000ft^2*	125.63 (11.67)	62.82 (5.84)
	10-19 units *apartments, 4-7 storeys, 60,000ft^2*	112.73 (10.47)	56.37 (5.24)
Professional/technical / business services	Office, small *2-4 storeys, 20,000ft^2*	102.69 (9.54)	102.69 (9.54)
	Office, medium *5-10 storeys, 80,000ft^2*	98.96 (9.19)	98.96 (9.19)
	Office, large *11-20 storeys, 260,000ft^2*	88.21 (8.19)	88.21 (8.19)
Hospital	Hospital, medium *2-3 storeys, 55,000ft^2*	144.60 (13.43)	216.90 (20.15)
	Hospital, large *4-8 storeys, 200,000ft^2*	125.60 (11.67)	188.40 (17.50)
Light Industrial	Warehouse, medium *30,000ft^2*	61.91 (5.75)	92.87 (8.63)
	Factory, small *1 storey, 30,000ft^2*	73.82 (6.86)	110.73 (10.29)
	Factory, large *3 storey, 90,000ft^2*	78.61 (7.30)	117.92 (10.95)

Table 4: Examples of replacement costs in 2002 figures, from HAZUS (2003)

7.3 Loss of functionality

The costs related to loss of functionality would be most significant for structures that are expected to function in rescue or emergency operations, following a failure event: for example hospitals, fire stations and power plants. The cost related to loss of functionality would be significantly less for residential structures, but not equal to zero due to cost of re-housing for example.

For a business, the loss of functionality could be computed from the lost gross domestic product (GDP) or the lost value added. The advantage of these approaches is that they are independent of the tax, social and juridical system of the considered country.

7.4 Clean up costs

The quantity, type and size of debris produced by the building collapse will determine the cost of removal and disposal. This will contribute significantly to the overall clean-up costs. Large debris, such as steel or reinforced concrete building elements, may require specialist handling to make them easy to transport. These elements would be considerably more expensive to clear than, for example, bricks or timber elements.

As the clean-up following a failure event will most likely be dealt with by the building contractor(s), this may already be included in the cost of repair/replacement. Therefore, care should be taken to ensure this factor is not accounted for more than once.

7.5 Rescue costs

The rescue cost is equal to the cost associated with providing emergency services (ambulance, fire brigade etc.). This may be estimated by taking the number of fatalities and injuries, and multiplying them by a suitable cost per person. These costs may also be included in the human consequences, as part of the injury cost.

7.6 Regional economic effects

In general, the effect of a single building failure on the regional economy tends to be short term and the cost may be small compared to some of the other categories examined herein. However, when evaluating the consequences of acts of terrorism (for example) these effects are likely to be significant.

In their study of the failure consequences of the collapse of the World Trade Centre Twin Towers, Faber, Kübler et al. (2004) provide a detailed outline of the steps involved in determining the impact of this event on the economy. The cost of business interruption is evaluated as the lost added value of the gross city profit (GCP), estimated by comparing the projected and real GCP. The economic cost related to job and wage losses are also evaluated. When the economic losses evaluated in four official reports are compared, the values range between 7.2 and 64.3 billion USD. This difference highlights the difficulties associated with estimating the cost of damage to the regional economy. In particular, the length of time considered should be carefully chosen, and economic expertise may be required to distinguish between normal/seasonal fluctuations and economic fluctuations as a result of structural failure. For further information, a detailed description of the methodologies for assessing the macro- and micro-economic effects of natural hazards can be found in Murlidharan (2003).

7.7 Cost of investigations/compensation

The cost of investigations/compensation is dependent on the structure type, use, occupancy and ownership among other factors. For example, the cost of the investigation into the collapse of a school building is likely to be much greater than the cost of the investigation into the collapse of an empty warehouse.

7.8 Loss of reputation

The loss of reputation may be taken as the long-term effect of a structural collapse on business activities. By studying the share value for a long period of time following the repair/replacement of a structure, this may be included in the effect on share prices term. Difficulties may arise when determining the time period to be considered. It is important this period is of adequate length to accurately assess these costs. Economic experience will most likely be required to evaluate this term.

8 Environmental Consequences

The failure of an engineering structure can have consequences for plants, animals and humans. This section addresses the CO_2 emissions and the cost of environmental studies/repair, as well as the release of toxic pollutants, following building failures.

8.1 CO_2 emissions/energy use

The amount of CO_2 emitted during the repair/replacement of the structure, and the increased (if any) emissions due to the loss of functionality (e.g. rail transport moves to road) should be computed. This is usually cited in tonnes of carbon, and difficulties may arise in converting this to a cost. A similar approach may be followed to determine the cost of energy used.

Mining and processing ore into steel is an energy intensive process, and hence steel is a significant contributor to CO_2 emissions. It is estimated that virgin steel produces 2.7 tonnes of CO_2 per tonne of steel, while recycled steel produces 0.4 tonnes of CO_2 per tonne of steel (Amos, 2010). NIFES (National Industrial Fuel Efficiency Limited) recommends an average value of 1.82 tonnes of CO_2 per tonne of steel.

The majority of carbon embedded in concrete is as a result of the cement manufacturing process: with the amount of CO_2 emitted dependent on the manufacturing process. One tonne of cement produces between 0.74 tonnes of CO_2 (dry kiln process) and 0.97 tonnes of CO_2 (wet kiln process) (Amos, 2010). An average value of 0.8 tonnes of CO_2 per tonne of cement can be used.

Typically, reinforced concrete contains 275-400 kg of cement/m^3 and 150-450 kg of reinforcement/m^3 (typical reinforcement in a RC column) (Cobb, 2004). Therefore, approximately 0.62-1.09 tonnes of CO_2 are emitted per cubic metre of reinforced concrete (or 0.26-0.45 tonnes of CO_2 per tonne of reinforced concrete, where density of reinforced concrete is 2400 kg/m^3).

Material	**Carbon emitted**
Steel	1820 Kg CO_2/te
Cement	800 Kg CO_2/te
Reinforced Concrete	260-450 Kg CO_2/te

Table 5: Carbon content of some typical building materials

The CO_2 emissions associated with transport can also be significant, and will be dependent on the distance travelled, journey composition (urban/rural/motorway), vehicle type and whether the vehicle is loaded or unloaded. The site fuel usage during any repair/replacement works may also be accounted for.

8.2 Environmental studies/repair

Finally, the cost of environmental studies, and any resulting reparative measures, will be dependent on the location and use of the structure.

8.3 Toxic releases

In special cases, the release of toxic pollutants may be a serious consequence of a building collapse, and extra care should always be taken to secure such pollutants. The cost of polluting the environment and harming the natural habitats of plants, animals and humans is difficult to estimate, but this is likely to be large only for buildings with special functions.

9 Discussion

This factsheet presents the range of, and discusses the variability in, the consequences of building failure due to accidental actions. These consequences are influenced by the nature of the hazard, properties of the structure, use/occupancy, location, meteorological conditions, the time frame considered and the scope of consequences considered. The different types of consequences (listed in Table 2) have been discussed in greater detail and suggested approaches for estimating the consequences have been outlined.

One of the current difficulties in developing and validating techniques to estimate the consequences of building failure, is that there is limited possibility to perform field studies (such as those used in earthquake loss estimation studies), due to a lack of case studies with sufficiently detailed information. In particular, reports on past failures often focus on the structural details of the failure and provide little in-depth information on the human, economic and environmental consequences. The collapse of the World Trade Centre Twin Towers is one of the first examples of a failure where a large amount of information is available on the various consequences (Faber, Kübler et al., 2004). If a detailed framework for estimating the consequences of building failures is to be developed, future reports on building failures should go some way towards providing the same level of detail.

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Appendix: Economic adjustments

Future values

Monetary values for the consequences of failure should be expressed in 'real terms' (i.e. at today's general price level). Therefore, for future costs, the effect of expected inflation in the general price level should be removed, by considering the cost of activities happening in the future using today's prices. Additionally, a cost to be encountered in the future needs to be discounted to account for the fact that people generally prefer to receive goods now than some time in the future. This is achieved by determining the net present value (NPV), by multiplying the cost (or benefit) encountered in the future by a discount factor, D_n.

$$D_n = \frac{1}{(1+r)^n} \tag{A1}$$

The discount factor is calculated using Equation A1, where r is the discount rate (presently recommended discount rate for public investments is 3.5%) and n is the number of years being discounted. For long-term discounting (greater than 30 years) a declining schedule of discount rates should be used (see HM Treasury).

Past values

In order to compare the costs that occur at different periods of time, the computed costs for the various consequences should be converted to a single currency, usually USD, using an appropriate conversion rate for the time of occurrence. For costs associated with different reference years, these costs should also be adjusted for inflation to the base year (often taken as 2000) before a valid comparison can be made. This can be achieved by multiplying the cost by a suitable inflation rate of a price index, usually the consumer price index, CPI. It is important to convert the costs to a single currency before accounting for inflation, to avoid inter-currency differences in inflation.