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Building Failure Consequences

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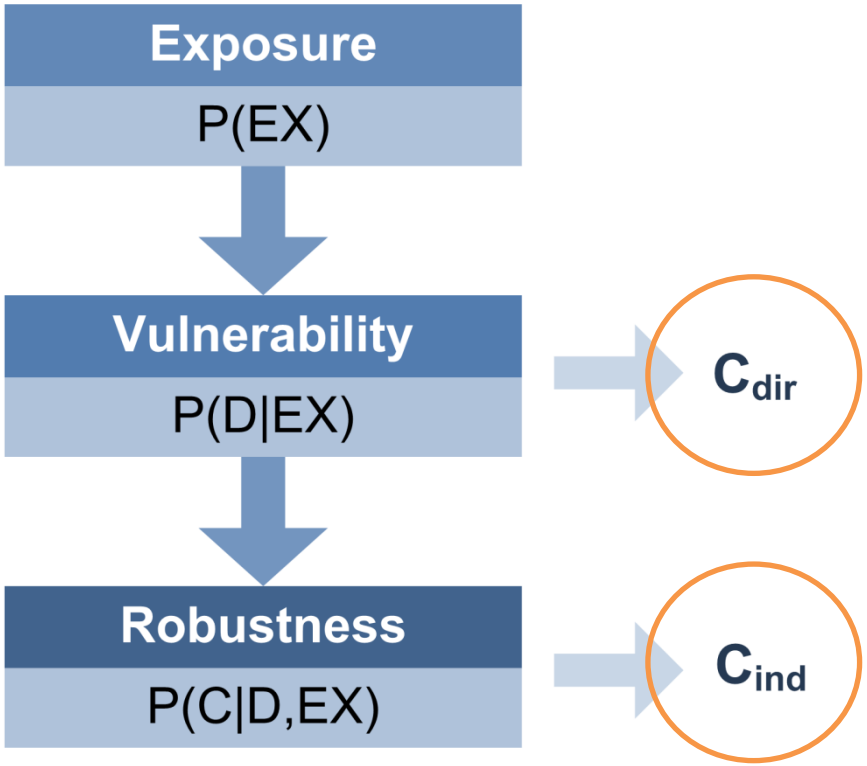
Introduction

- Consequences:- "the possible result[s] of an (in risk analysis usually unwanted) event" EN 1991-1-7.
- Building failure consequences can come in many forms e.g. fatalities, structural damage, loss of functionality etc.
- Often divided into two categories (according to the *system boundary definition*):
  - **Direct consequences** are those resulting from damage states of individual component(s)
  - **Indirect consequences** are related to a loss of system functionality or failure, as a result of local failure

Introduction



$$R = \sum_i \sum_j C_{dir,ij} P(D_j|EX_i)\, P(EX_i) + \sum_k \sum_i \sum_j C_{ind,ijk} P(C_k|D_j \cap EX_i)\, P(D_j|EX_i) P(EX_i)$$

Influencing factors

The consequences of failure vary significantly from structure to structure, and may depend on:

- Nature of the hazard
- Properties of the structure
- Use/occupancy
- Location
- Time of day
- Time frame considered

Failure consequences & the Eurocodes

- EN1991-1-7 classifies buildings according to their consequences of failure to determine how accidental design situations should be dealt with
  - 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**

Failure consequences & the Eurocodes

Consequence Class	Example of categorisation of building type and occupancy
1	Single occupancy houses less than 5 storeys. Agricultural buildings. Buildings into which people rarely go.
2a (lower risk group)	5 storey single occupancy houses. Multiple occupancy residential buildings and offices less than 5 storeys. Retail buildings less than 4 storeys, up to 1000 m^2 floor area/storey. All public buildings less than 3 storeys, up to 2000 m^2 floor area/storey.
2b (Upper risk group)	Multiple occupancy residential buildings and offices from 5 to15 storeys. Retailing premises from 4 to15 storeys. All public buildings with between 2001 m^2 and 5000 m^2 floor area/storey.
3	Buildings not meeting the lesser requirements for classes 1 or 2. Buildings admitting people in significant numbers. Buildings containing hazardous substances and/or processes.

Classification of damage severity

- Level of damage can be used to estimate consequences
- Consistent measure of damage severity is required
- A number of models exist relating the level of damage following earthquakes to the observed consequences e.g. the European Macroseismic Scale (EMS)
- These approach could be adapted and applied to building failures caused by accidental actions

Classification of damage severity

Grade	Damage Level	*% 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%*

EMS damage grades

Proposed classification for damage resulting from accidental actions

Classification of consequences

	Direct Consequences	Indirect Consequences
Human	Injuries Fatalities	Injuries Fatalities Psychological Damage
Economic	Replacement/repair of initial damage Replacement/repair of contents Clean up costs Rescue costs	Replacement/repair of structure Replacement/repair of contents Clean up costs Rescue costs Loss of functionality Regional economic effects Investigation/compensation
Environmental	CO_2 Emissions Energy use Toxic releases	CO_2 Emissions Energy use Toxic releases Environmental Studies/Repair
Social		Loss of reputation Changes in professional practice

Human Consequences

Human Consequences

FATALITIES

- Coburn, Spence et al. developed a model for predicting fatalities as a result of building collapse following earthquake
- For a class of building, *b*, the authors defined the number of people killed, K_s, as

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

Human Consequences

FATALITIES

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

- $D5_b$ is the total number of collapsed structures of building type b

Human Consequences

FATALITIES

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

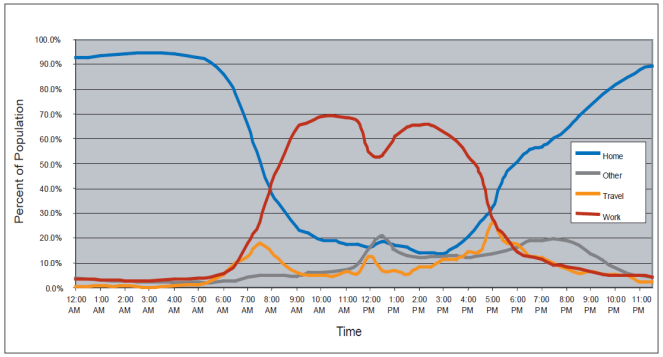
- *M1* is the number of people per building type *b*

Human Consequences

FATALITIES

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

- *M2* represents the percentage of the people in the building at collapse
- Determined using detailed occupancy level graphs or average values



Typical average daily occupancy levels (Nathwani, Lind et al., 1997)

Residential urban	65%
Non-residential urban	40%
Rural agricultural	45%

Human Consequences

FATALITIES

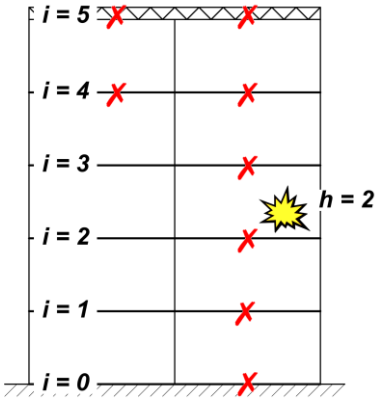
$$Ks_b = D5_b * [M1_b * M2_b * M3_b * (M4_b + M5_b)]$$

- *M3* accounts for the fact only a portion of the occupants will be trapped by the resulting damage/collapse
- For building collapse due to accidental actions,

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

- For damage levels *D4-5*, and when the time to collapse is relatively small

$$\alpha = 1.0 \text{ , } \beta = 1 - 0.5/h$$



Human Consequences

FATALITIES

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

- *M4* signifies the number of people killed instantly by the collapse, as a percentage of *M3*
- For earthquakes, and depending on the type of building, Coburn gave the following value for *M4*

Masonry	0.2
Reinforced concrete	0.4

- Further studies required to quantify this value for failure resulting from accidental actions

Human Consequences

FATALITIES

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

- *M5* is the post-collapse mortality factor
- Dependant on the severity of injuries caused by collapse
- Can be considered a measure of effectiveness of the rescue operations/medical activities
- For earthquakes, and depending on the type of building, Coburn gave the following ranges of values for *M5*

Masonry	0.45 - 0.90
Reinforced concrete	0.70 - 0.90

Human Consequences

FATALITIES

- The number of fatalities can be used directly as a measure of the consequences of building collapse
- Otherwise, to quantify the fatalities in monetary terms, we must quantify the 'economic' value of human life:
  - Value of statistical life
  - Money spent on government programmes per life saved
  - Willingness to pay approach (WTP)
  - Earnings lost due to premature death
  - Life Quality Index (LQI)
  - Large range of values cited, a mean of €1-2m is often used

Human Consequences

INJURIES

- Cost of injuries may include:
  - Pre-hospital emergency treatment
  - Emergency department services
  - Hospital physician and surgeon services
  - Visits to private physicians
  - Rehabilitation costs
  - Loss of earnings
  - Compensation for pain and suffering

Human Consequences

Injuries

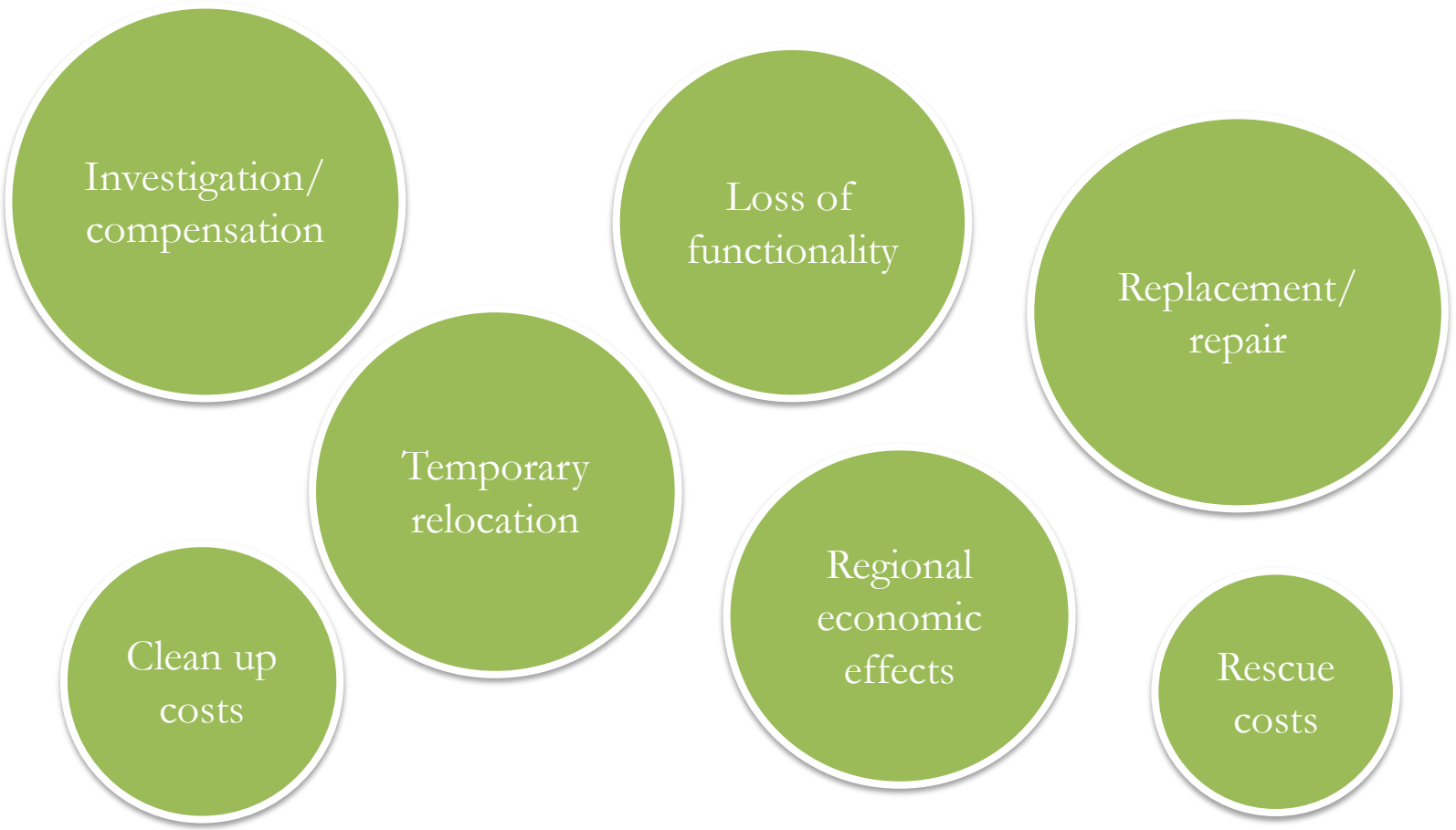
- The type of injuries observed (and their severity) is dependant on:
  - The hazard
  - The resulting level of damage
  - The building type
- Research undertaken in medical profession and in the field of earthquake engineering forms a good starting point

Human Consequences

PSYCHOLOGICAL DAMAGE

- Experienced by persons injured/exposed to event (and possibly the relatives of any person killed/injured)
- Psychological effects summarised by Faizian et al. as fear, helplessness, distress and depression
- Dependant on:
  - Type/severity of injury
  - Buildings use (Kanda and Shah)
  - Loss/damage caused (Faizian et al.)
- May be included in injury cost or dealt with seperately

Economic Consequences



Economic Consequences

REPLACEMENT/REPAIR

- Replacement/repair of structural components (structural consequences)
  - Depends on the extent of damage, structure type, size etc.
  - Should account for **all building components**
- Replacement/repair of its contents (non-structural consequences)
  - Depends on the extent of damage, nature of contents, market price etc.
- HAZUS building replacement cost models (US$/$m^2$)

Economic Consequences

CLEAN-UP COSTS

- Cost of removal and disposal is dependant on quantity, type and size of debris
- May be included in the cost of repair/replacement (*beware of double counting*)

Economic Consequences

RESCUE COSTS

- Cost associated with providing emergency services (ambulance, fire brigade etc.)
- Estimated by taking the number of fatalities and injuries, and multiplying them by a suitable cost per person
- May be included in human consequences, as part of the injury cost (*beware of double counting*)

Economic Consequences

Loss of functionality

- Greatest for structures that must function in emergency operations, following a failure event (e.g. hospitals, fire stations, power plants etc.)
- For a business, could be computed from the lost gross domestic product (GDP) or lost value added
- Temporary relocation

Economic Consequences

REGIONAL ECONOMIC EFFECTS

- For a single building failure due to non-malicious actions the economic effect tends to be short-term and a relatively minor consequence
- Significant for failures arising from malicious actions
  - E.g. collapse of the WTC Twin Towers
- Compare an economic indicator (e.g. GCP) before and after the event
- Include job and wage losses
- Highly variable and may require economic expertise

Economic Consequences

COST OF INVESTIGATIONS/COMPENSATION

- Dependent on the structure type, use, occupancy, ownership etc.

Environmental Consequences

Environmental Consequences

CO_2 EMISSIONS/ENERGY USE

- During repair/replacement of the structure
- Increased emissions (if any) due to loss of functionality
- Site fuel usage during repair/replacement works may also be accounted for
- CO_2 emissions usually cited in tonnes of carbon - difficulties may arise when converting this to a cost

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

Environmental Consequences

TOXIC RELEASES

- Cost of polluting the environment, and harming the natural habitats of plants, animals and humans
- Likely to be large only for buildings with special functions

Environmental Consequences

ENVIRONMENTAL STUDIES/REPAIR

- Dependent on the location and use of the structure
- May be able to estimate by studying similar examples

Social Consequences

Social Consequences

Loss of reputation

- Long-term effect (how long?) of a structural failure on business activities
- May be included in the economic effects (*beware of double counting*)
- Again may require economic expertise to determine

Social Consequences

CHANGES IN PROFESSIONAL PRACTICE

- Building failures may lead to less conservative safety requirements – increase in cost
- May discourage certain method of construction/use of material etc.
- Difficult to anticipate when performing a pre-emptive consequence analysis

Discussion

- The range of consequences of building failure due to accidental actions and their influencing factors have been discussed
- Approaches for estimating some types of consequences have been outlined
- Difficulties in performing a consequence analysis arise from limited information for collapse due to accidental actions
  - Learn from earthquake engineering
  - Future reports on building failures should include details on consequences

Acknowledgement

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Thank You