Structural robustness of buildings
Sureswaran Thirunavukkarasu, Senior Engineer Structures

March 2016
Robustness

In structural terms:

• Robustness is defined as the ability of a structure to withstand events like fire, explosions, impact or consequences of human error, without being damaged to an extent disproportionate to the original cause.

• From the above definition it can be concluded that structures designed and constructed to have robustness will not suffer from disproportionate collapse.
Progressive and disproportionate collapse of Ronan Point apartments, East London, UK

- The 22 storey apartment block was constructed using prefab concrete panels
- Partial collapse of one corner, triggered by an internal gas explosion on the 18th floor, collapsed over nearly its entire height (London, 1968)
- 4 people killed and 17 injured
- The building suffered partial collapse disproportionate to the cause
- Cause: Poor design and construction
- Major changes in UK building regulations resulted.
Progressive collapse of Alfred P Murrah Building, Oklahoma City, USA

- Housed approximately 550 employees
- Half of building collapsed seconds after truck bomb in 1995
- 168 people killed
- Every second interior column rested on transfer girder that ran across the perimeter of the structure at second floor
- Collapse did not progress to the last bay where there was a discontinuity of top reinforcement of the transfer girder
- Lack of redundancy/ alternative load paths to redistribute the loads to neighbouring main columns
Progressive collapse of Sampoong department store, Seoul, South Korea

- Collapsed in 1995
- Over 500 people killed and over 900 people injured
- Structural modifications made during its lifetime contributed
- Some causes: A fifth floor was added to house a restaurant which involved installation of a heavy concrete slab, heavy air conditioning (approx. 17t) units were dragged across the roof and relocated, undersized columns
- A section of the building came crashing down into the basement in less than 20 seconds
Tacoma Narrows Bridge, USA

- In 1940, cable-stayed bridge collapsed due to wind-induced distortions of the bridge girder.
- Zipper-type collapse triggered by initial failure of a single cable and progressing due to resulting overloading and failure of adjacent cables.
- To prevent such a failure, it is recommended that loss-of-cable load cases should be included in the structural analysis.
Structural robustness of buildings

• Building regulations all over the world addressed robustness issues in the design of tall/large occupancy buildings following Ronan Point incident.
• After the Ronan Point collapse, British standards have a long tradition of addressing robustness in the design of buildings.
• Design for avoidance of disproportionate collapse is a requirement in building structural standards.
• However, the robustness issue against progressive collapse is not yet consistently embodied in the structural standards.
Structural robustness of buildings

BCA Performance requirements

• A building or structure, during construction and use, must be designed to sustain local damage, with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage and to avoid causing damage to other properties.

• BCA Performance Requirements BP1.1 to BP1.4 can be satisfied if the deemed-to-satisfy provisions are complied.

• BCA deemed-to –satisfy provisions refer to AS1170 for further details on structural design requirements for robustness.
Robustness requirement in accordance with AS 1170.0

- Australian standard AS 1170.0 Section 6 deals with structural robustness.
- Structures shall be detailed such that all parts of the structure shall be tied together both in the horizontal and vertical planes so that the structure can withstand an event without being damaged to an extent disproportionate to that event.
- The design of the structure shall provide load paths to the foundations for forces generated by all types of actions from all parts of the structure.
- The structure shall have a minimum lateral resistance equivalent to 1.0 to 1.5 % of \((G+\psi_cQ)\), depending on the height of the building, applied simultaneously at each level for a given direction. The direction of application of the lateral load shall be that which will produce the most critical action effect in the element under consideration.
- Connections shall be capable of transmitting 5% of the value of \((G+\psi_cQ)\) for the connection under consideration.

Note: \(\psi_c\) - combination factor for imposed action
Robustness requirement in accordance with Eurocode

Eurocode design strategies

**Figure 3.1 - Strategies for Accidental Design Situations**

NOTE 1: The strategies and rules to be taken into account are those agreed for the individual project with the client and the relevant authority.

NOTE 2: Accidental actions can be identified or unidentified actions.

NOTE 3: Strategies based on unidentified accidental actions cover a wide range of possible events and are related to strategies based on limiting the extent of localised failure. The adoption of strategies for limiting the extent of localised failure may provide adequate robustness against those accidental actions identified in 1.1.1(c), or any other action resulting from an unspecified cause. Guidance for buildings is given in Annex A.

NOTE 4: Notional values for identified accidental actions (e.g. in the case of internal explosions and impact) are proposed in this part of EN 1991. These values may be altered in the National Annex or for an individual project and agreed for the design by the client and the relevant authority.

NOTE 5: For some structures (e.g. construction works where there is no risk to human life, and where economic, social or environmental consequences are negligible) subjected to accidental actions, the complete collapse of the structure caused by an extreme event may be acceptable. The circumstances when such a collapse is acceptable may be agreed for the individual project with the client and the relevant authority.
Robustness requirement in accordance with Eurocode

Eurocode design strategies for accidental actions are:

1. Strategies based on identified accidental actions
2. Strategies based on unidentified accidental actions
Robustness requirement in accordance with Eurocode

Strategies for identified accidental actions

• A localised failure due to accidental actions may be acceptable provided it will not endanger the stability of the whole structure and allows the necessary emergency measures to be taken. These emergency measures may involve the safe evacuation of persons from the premises and its surroundings.

• Measures should be taken to mitigate the risk of accidental actions and these measure should include one or more of the following:

  1. Preventing the action from occurring (e.g. forbidding the use of gas and storing explosive materials in the building)
  2. Reducing the probability and/ or magnitude of the action to an acceptable level through structural design process (e.g. providing sacrificial venting components with low mass and strength to reduce the effect of explosions)
  3. Protecting the structure against the effects of an accidental action by reducing the effects of the action on the structure (e.g. protective bollards, or safety barriers against vehicle impact)
  4. Ensuring that the structure has sufficient robustness by (a) designing certain components of the structure on which stability depend as ‘key elements’ (b) designing structural members to have sufficient ductility capable of absorbing significant strain energy without rupture (c) incorporating sufficient redundancy in the structure to facilitate the transfer of actions to alternative load paths.
Robustness requirement in accordance with Eurocode

Strategies based on unidentified accidental actions

• Potential failure of the structure arising from unspecified cause shall be mitigated
• The mitigation should be reached by adopting one or more of the following approaches:

  1. Designing key elements, on which the stability of the structure depends, to sustain the effects of accidental actions. (British National Annex to the Eurocode recommends a uniformly distributed load of 34 kN/m² for designing key elements in building structures)

  2. Designing the structure so that in the event of a “localised failure” the stability of the whole structure or significant part of it would not be endangered (British National Annex states the acceptable limit of localised failure as 100m² or 15% of the floor area whichever is less, on two adjacent floors caused by the removal of any supporting column, pier or wall)

  3. Applying prescriptive design/detailing rules that provide acceptable robustness for the structure (example—three dimensional tying for additional integrity, or a minimum level of ductility of structural members subject to impact)
Horizontal tying

Horizontal tying is beneficial to a structure in an accidental action situation by:

- Enabling catenary action to develop-
  the principle of providing horizontal ties allows for beam members to support loads by forming catenaries over damaged areas of structure
- Holding columns in place-

Accidental actions can cause horizontal forces to act on column sections. Ensuring that beam-to-column connections have tying resistance helps to hold the column in place and therefore that it can continue to support vertical loads.
Horizontal and vertical tying

- Horizontal and vertical tying allows to redistribute the forces vertically as well as horizontally.
- Horizontal ties should be provided around the perimeter of each floor/roof and internally in two right angle directions to tie the columns in continuous lines.
- Taller buildings require vertical as well as horizontal tying.
- When tying is not possible the structure should be designed to bridge over a loss of a supporting column or wall by catenary action.
Notional removal design strategy

- The notional removal design strategy for robustness in Eurocode is presented as an alternative to the provision of horizontal and vertical tying.
- The benefits of this design strategy are that instead of following prescriptive rules (e.g., tying), more specific damage scenarios are considered.
- This design strategy will generally be successful for small column spacings.
- This design strategy can be useful if for some reason it is not possible to comply fully with tying rules.
- In the above method, each member should be removed one at a time to ensure that the limit of admissible local damage shown in the diagram above is not exceeded.
- Progressive collapse potential is limited if the damaged area is smaller than 15% of the area of the storey or 100m² whichever is smaller.
Notional removal design strategy

- To ensure the damage does not spread down the building, the floor beneath the collapsed floor should be checked to ensure that it does not collapse due to the debris load from the floor above falling onto it.
- To ensure the damage does not spread up the building, the floors above the removed column should be checked to determine whether they can bridge over the removed column.
- Without the horizontal and vertical tying and sufficient systems capable of resisting lateral forces the floors above will also collapse.
Key element design

- Key element design approach may be applied where notional removal of supporting member would result in admissible damage limit being exceeded.
- If not possible to develop catenary action or bridge over missing member, this member must be designed as a key element to withstand the load generated by an abnormal event (in the case of Ronan Point gas explosion the additional load is derived as 34 kN/m²).
- The key element approach is fundamentally different from the tying approach and the notional removal approach.
- Tying and notional removal approaches focused on limiting the spread of damage following event where supporting element to be damaged.
- The key element approach is focused on preventing the supporting element being damaged following an accidental event.
- Recommended accidental design action for building structures is 34 kN/m².

Note: In recent years both the UK and EU have introduced a risk based design approaches for abnormal incidents. Depending on the building types, occupancy, buildings assigned consequence classes.
Summary on BCA and AS/ NZS1170.0 requirements

BCA/ Australian standard AS/ NZS 1170.0 requirements:

- All parts of structures shall be tied in horizontal and vertical planes
- Structure shall provide load paths to foundations for forces generated by all types of actions
- Structure shall have minimum lateral resistance equivalent to 1.0% to 1.5% of vertical dead loads and reduced vertical live loads
- Minimum lateral resistance of all connections shall be capable of transmitting 5% of the vertical dead loads and reduced vertical live loads acting on the connections
- Prescriptive rules (indirect design) used
- Performance based structural design (direct design) not considered in AS1170.0 for robustness
- A risk based approach not used
Summary on Eurocode requirements

Eurocode EN 1991-1-7 requirements:
• Prevent the action from happening
• Protecting the structure against the effects of the accidental actions
• Ensuring that the structure has sufficient robustness by adopting one or more of the following approaches:
  – Effective horizontal and vertical ties in accordance with the structural codes of practice
  – Where the above provisions could not be made, it was recommended that the structure should be able to bridge over the loss of a member and the area of collapse to be limited and localised
  – If it is not possible to bridge over the missing member such member should be designed as a “key element” capable of resisting addition loads related to 34kN/m2
  – By designing structural members, and selecting materials, to have sufficient ductility, capable of absorbing significant strain energy without rupture
Conclusions

- Eurocode provides both performance based and prescriptive requirements to address the robustness issues in buildings by considering the identified and un-identified accidental actions.

- BCA provides performance based requirements.

- The deemed-to-satisfy structural provisions in BCA mainly refers to AS/NZS1170 for compliance on structural robustness which is only dealt with using prescriptive rules on minimum lateral resistance of the building and its connections.

Are the prescriptive rules given in AS standards adequate to mitigate the risks due to accidental actions?
Questions?