SIXTEEN MARKS

1. Define abnormal loads. Explain the causes of progressive collapse? (April/May 2011)

ABNORMAL LOADS:

Loads other than conventional design loads (dead, live, wind, seismic, etc.) for structures such as air blast pressures generated by an explosion or impact by vehicles, etc.

CAUSES OF ABNORMAL LOADS:

1. Accidental impact
2. Faulty construction
3. Foundation Failure
4. Violent changes in Air pressure.

(i) ACCIDENTAL IMPACT:

Several cases of progressive collapse have been caused by accidental impact. An example of this form of abnormal loading is an automobile striking a key member in a structure (i.e. buildings, bridge etc)

(ii) FAULTY CONSTRUCTION:

- There have been several instances throughout history where poor construction practices have lead to progressive collapse.
- A notable example of this was the skyline plaza apartment in Fairfax County, Virginia.
- This failure was attributed to premature removal of supporting forms.
- This lead to localized failure, followed by a progressive collapse of the northwest corner of the building.

(iii) FOUNDATION FAILURE:

- Failure of a small portion of a structures foundation can result in a loss of primary support.
- This failure could be the result of problems with erosion, geology, catering due to explosion etc.,
- If the remainder of the structure is unable to redistribute this change in load caused by the loss in support, extensive damage to the structure could be much greater.

(iv) VIOLENT CHANGES IN AIR PRESSURE:

An extreme change in air pressure can stem from any sources such as explosions caused by gas, high explosives etc.,

- An example of a progressive collapse that resulted from a sever change in air pressure was the 1995 terrorist bombing of the A.P.Murrah Federal building in oklahoma city, oklahoma.

Importance of avoidance of progressive collapse: (Nov/Dec 2013)

Progressive collapse avoidance has several advantages:

- Provides a solid exterior surface to meet blast resiliency requirements
- Delivers the inherent strength of concrete tilt-up panels for overall durability
- Minimizes cost to fix a damaged area compared to a steel framed building
- Eliminates perimeter stell leading to greater interior space planning flexibility.

2. Explain the codal provisions for Progressive collapse. (Nov/Dec 2013) (May/June 2012)

The following are the codal provisions for progressive collapse

1. ASCE 7-02
2. ACI 318-02
3. GSA PBS facilities standards 2000
4. GSA PBS facilities standards 2003
5. GSA PBS progressive collapse guidelines 2003.

1. ASCE 7 -02:

- The American society of civil engineers, minimum design loads for buildings and other structure (ASCE,2002) has a section on "general structure integrity" that reads thus: Building and other structures Shall 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.
- This shall be achieved through an arrangement of the structural elements that provides stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse.
- This shall be accomplished by providing sufficient continuity, redundancy, or energy-dissipating capacity (ductility) or a combination there of in a members of the structure.

- Clearly, the focus in the ASCE standard is on redundancy and alternate load paths over all other means of avoiding susceptibility to disproportionate collapse.
- But the degree of redundancy is not specified and the requirements are entirely threat -independent

2. ACI 318 -02:

- The American concrete institution building code requirements for structural concrete (ACI, 2002) include extensive "Requirement for structural integrity" in the chapter on reinforcing steel details.
- Though the commentary states that it "is an intend of this section to improve redundancy "there is no explicit mention of redundancy or alternate load paths in the code.
- The code provisions include a general statement that "In the detailing of reinforcement and connections, members of a structure shall be effectively tied together to improve integrity of overall structure" and many specific prescriptive requirements for continuity of reinforcing steel and interconnection of components.
- There are additional requirements for the tying together of precast structural components.
- None of the ACI provisions are threat specific in anyway.

3. GSA PBS Facilities Standards 2000:

- The 2000 edition of the GSA's facilities standards for the public building service (GSA 2000) included the following statement under the "progressive Collapse" heading in the "Structural Considerations" section. "The structure must be able to sustain local damage without destabilizing the whole structure. The failure of beam, slab, or column shall not result in failure of the structural system below, above, or in adjacent bays. In case of column failure, damage in the beams and girder above the column shall be limited to large deflections. Collapse of floors and roofs must not be permitted.
- This is an absolute and unequivocal requirement for one-member (beam, slab or column) redundancy, unrelated to degree of vulnerability of the member or the level of treat to the structure.

4. GSA PBS facilities standards 2003:

- The 2003 edition of the GSA's facilities standards for the public buildings service (GSA, 2003) retained the "Progressive Collapse" heading from the 2000 edition, but replaced all of the words reproduced above with this short statement " Security Design".
- The structural provisions apply only to buildings deemed to be at risk of blast attack.
- For such buildings, the chapter provides general performance guidelines and references to various technical manuals for the study of blasts effects.
- This represents a complete change of approval from the 2000 version of the same document.

5. GSA PBS Progressive Collapse Guidelines 2003:

- The GSA Progressive collapse analysis and design guidelines for new federal
- Buildings and major modernization projects(GSA,2003b) begins with a process for determining whether a building is exempt from Progressive Collapse considerations.
- Exemption is based on the type and size of the structure (for instance any building of over 10 stories is non-exempt) and is unrelated to the level of threat.
- Typical non-exempt buildings in steel or concrete have to be shown by analysis to be able to tolerate removal of one column or one-30 ft length of bearing wall without collapse.
- Considerable detail is provided regarding the features of the analysis and the acceptance criteria.
- In some ways, these guidelines appear to be a throw-back to the GSA's PBS. Facilities standards of 2000 in that their central provision is a requirement for one-member redundancy, unrelated to the degree of vulnerability of the member or the level of threat of the structure.

3. Explain the methods of preventing disproportionate collapse.

METHODS OF PREVENTING DISPROPORTIONATE COLLAPSE:

There are three alternative approaches in designing the structure to reduce their susceptibility to disproportionate collapse.

1. Redundancy or Alternate load paths.

2. Local resistance

3. Interconnection or continuity.

1. **Redundancy or Alternate load paths:**

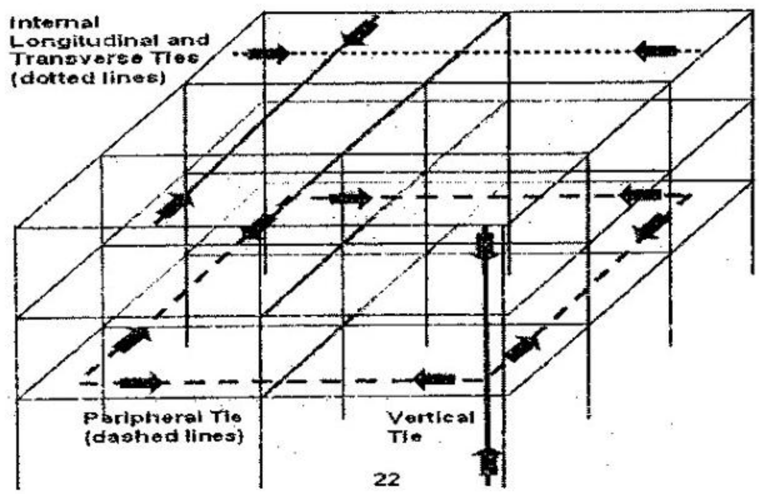
   - In this approach, the structure is designed such that if any one component fails, alternate paths are available for the load in that component and a general collapse do not occur.
   - This approach has benefit of simplicity and directness.
   - In most common applications, design of redundancy requires that a building structure be able to tolerate loss of any one column with collapse. This is an objective, easily –understood performance requirement.
   - The problem with the redundancy approach, as typically practiced, is that it does not account for differences in vulnerability.
   - Clearly, one – column redundancy when each column is a W8 X35 does not provide the same level of safety as when each column is a 2000lb/ft built up section.
   - Indeed, an explosion that could take out the 2000lb/ft column would likely to destroy several of the W8 columns, making one-column redundancy inadequate to prevent collapse in that case.
   - And, yet codes and standards that mandate redundancy of small and lightly loaded column, redundancy requirements may have the unfortunate consequence of encouraging designs with many small columns rather than fewer larger columns.

2. **Local Resistance:**

   - In this approach, susceptibility to progressive collapse is reduced by providing critical components that might be subject to attack with additional resistance to such attacks.
   - This requires some knowledge of the nature of potential attacks.
   - And it is very difficult to codify in a simple and objective way.

3. **Interconnection or Continuity:**

   - This method of approach is a mean of improving either redundancy or local resistance or both.
   - Studies of many recent building collapses have shown that the failure could have been avoided or at least reduced in scale, at fairly small additional cost, if the structural components are interconnected more effectively.
   - This is the basis of the "Structural Integrity" requirements in the ACI 318 specifications.



4. Explain the Guidelines for achieving Structural integrity.

1. **Connections between structural components should be ductile** and have a capacity for relatively large deformations and energy absorption under the effect of abnormal conditions.

2. **Good Plan Layout:**

An important factor in achieving structural integrity is the proper plan layout of walls and columns.

In bearing walls structures there should be an arrangement of interior longitudinal walls to support and reduce the span of long sections of cross wall. Thus enhancing stability of individual walls and of the structure as a whole.

3. An Integrated System:

Provide an integrated system of ties among the principal elements of the structural systems. These ties may be designed specifically as components of secondary load-carrying.

4. Return on Walls:

Returns of interior and exterior walls will make them more stable.

5. Interior Explosion:

When explosions occur within structures pressures can build up within confined spaces, causing lightly attached wall, floor and roof surfaces to be blown away.

6. Changing directions of span of floor slab:

Where a one way floor slab is reinforced to span in main direction, provided spanning capability in its secondary direction also perhaps using a lower safety factor.

With this approach, the collapse of the slab will be prevented and the debris loading of other parts of the structure will be minimized.

Often, shrinkage and temperature steel may be enough to enable the slab to span in the secondary direction.

4. Give some examples of Progressive / Disproportionate collapse.

1. Ronan Point:

In May 1968, a gas explosion occurred in the newly occupied 24-storey Ronan Point apartment building, located in London, England. The explosion took place in an apartment kitchen near one corner of the building at 18th floor level. The blast blew out a primary supporting exterior bearing panel which led to loss of support for the floors above. This in turn began a chain reaction of collapse, upwards to the roof level. As a result of the loading generated by falling debris, lower floor also collapsed.

Construction of the Ronan point complex primarily consisted of precast panels. While this type of construction can be designed to avoid progressive collapse from abnormal loading conditions. The Ronan Point complex lacked the connection details necessary to effectively redistribute load. The essential training detail from this England apartment building was reinforcement continuity between panels. Because of this there was no mechanism in place for achieving alternatives load paths once failure began to propagate.

2. A.P. Murrah Federal Building:

In the morning of April 19,1995, a terrorist bombing was directly at the 9-storey A.P. Murrah Federal Building in Oklahoma city. This attack significant loss of life and inflicted many injuries to the occupants of this GSA facilities. The vast majority of the deaths were attributed to falling debris generated by the progressive collapse that the structure underwent. When the bomb detonated, primary support columns along the perimeter were locally damaged. The localized damage of these bearing members initiated a series o failures that extended across much of the north face and though the width of the building in the eastern part of the structure.

The primary structure of the A.P. Murrah Federal Building consisted of reinforced concrete ordinary moment frame with typical bay size of 20ft by 35ft. An important structural feature of the building was the use of transfer girder at the 3rd floor level. The girder provided support for intermediate columns that extended from the 3rd floor to the roof level. However, from the first floor to the third floor, there was a 40ft column spacing (as opposed to the 20ft spacing above the 3rd floor level. Hence, the loss of a column along the ground level created an 80ft unsupported length. It is believed that this was a primary mechanism that caused the progressive collapse of the building. This type of a structural feature is typically avoided when considering abnormal loads, since the use of transfer girder can potentially limit the building ability to effectively redistribute load. The GSA security criteria explicitly prohibit the use of transfer girders in the design of GSA facilities.

3. World trade centre 1 and 2:

Each of the twin towers of the world trade centre 1&2 collapsed on 11th September 2011 following this sequence of events: A Boeing 767 jetliner crashed into the tower at high speed. The crash caused structural damage at and near the point impact zone lost its ability to support the load above it, as a result of some combination of impact damage and fire damage. The structure above collapsed, having lost its support, the weight and impact of the collapsing upper part of the tower caused a progression of failures extending downward all the way to the ground.

Clearly, this was a "progressive collapse" by any definition. But it cannot labeled a " Disproportionate Collapse".It was a very large collapse caused by very large impact and fire.And unlike the case with Murrah building, simple changes in the structural design that might have greatly reduced the scale of the collapse have not yet been identified.

5. Write the design criteria for progressive collapse in abnormal loads.

In the assessment of a particular structure with regard to its collapse resistance, the following design criteria are of importance:

a. **Requirements**

b. **Design objectives**

c. **Design strategies**

d. **Verification procedures**

First, the requirements, particularly the question if collapse resistance is necessary, should be clarified. The necessity depends on the structure's significance with respect to the consequences of a collapse, including the immediate material and immaterial losses but also indirect effects, e.g., the possible impairment of the infrastructure and of civil and national defense. Another criterion for the determination of requirements is the structure's degree of

Exposure to hazards of war, malicious action, and natural disasters. The exposure can be considered particularly high for public buildings, major bridges, and other lifeline structures. If collapse resistance is deemed necessary, the following design objectives must be specified:

1. Assumable extent of accidental circumstances
2. Assumable extent of initial local failure
3. Acceptable extent of collapse progression
4. Acceptable extent of damage to the remaining structure
5. Applicable load combinations and safety factors

The following design strategies to prevent progressive collapse are mentioned in the literature and have at least partially made their way into the design codes:

1. High safety against local failure

1.1. Specific local resistance of key elements (direct design)

1.2. Non-structural protective measures (event control)

2. Design for load case "local failure" (direct design)

2.1. Alternate load paths

2.2. Isolation by compartmentalization

3. Prescriptive design rules (indirect design)

These methods are further discussed in Section 4 below. The prediction of the structural behavior following a local failure requires suitable verification procedures

. Accurate analysis will require a high degree of expertise and modeling effort. Thus, development and validation of simplified but admissible verification methods would be a worthwhile undertaking. The design criteria I. to IV. Listed above are to date only partially addressed in codes and guidelines. As far as applicable design criteria are not available in codified form, they should be agreed upon by the contracting and other affected parties or established by the building authorities. It is anticipated that the design criteria can only partly be developed from first principles and reliability theory.

There will remain necessity for judgment and a decision-making process, most notably when stipulating the acceptable extent of collapse progression. On the other hand, the choices to be made here are relatively transparent—at least when compared to the choice of a safety index

B so that an informed societal consensus is in principle possible (even when that consensus leads to the conclusion that certain kinds of structures should better not be build).

6. Explain the procedure for calculating equivalent design loads when the structure is subjected to earthquake loading. (May/June 2009) (May/June 2013)

The seismic loads on the structure during an earthquake result from inertia forces which were created by ground accelerations. The magnitude of these loads is a function of the following factors: mass of the building, the dynamic properties of the building, the intensity, duration, and frequency content of the ground motion, and soil-structure interaction.

In recent years, a lot of achievements have been made to incorporate these influential factors into building codes accurately as well as practically. The basis for IBC 2000 seismic provisions is the 1997 NEHRP "Recommended Provisions for the Development of Seismic Regulations for New Buildings and Other Structures" (FEMA 302).

The National Earthquake Hazard Reduction Program (NEHRP) is managed by the Federal Emergency Management Agency (FEMA).In IBC 2000, the seismic loads are on a strength level limit state rather than on a service load level, which was used in UBC 94 and prior versions. The seismic limit state is based upon system performance, not member performance, and considerable energy dissipation through repeated cycles of inelastic straining is assumed.

Criteria Selection

In IBC 2000, the following basic information is required to determine the seismic loads:

1. Seismic Use Group According to the nature of Building Occupancy, each structure is assigned a Seismic Use Group (I, II, or III) and a corresponding Occupancy Importance (I) factor (I ▯ 1.0, 1.25, or 1.5).Seismic Use Group I structures are those not assigned to either Seismic Use Group II or III. Seismic Use Group II are structures whose failure would result in a substantial public hazard due to occupancy or use. Seismic Use Group III is assigned to structures for which failure would result in loss of essential facilities required for post-earthquake recovery and those containing substantial quantities of hazardous substances.

2. Site Class Based on the soil properties, the site of building is classified as A, B, C, D, E, or F to reflect the soil-structure interaction. Refer to IBC 2000 for Site Class definition.
3. Spectral Response Accelerations SS and S1 The spectral response seismic design maps

reflect seismic hazards on the basis of contours. They provide the maximum considered earthquake spectral response acceleration at short period SS and at 1-second period S1. They are for Site Class B, with 5% of critical damping. Refer to the maps in IBC 2000.

4. Basic Seismic-Force-Resisting System Different types of structural system have different energy-absorbing characteristics. The response modification coefficient R in Table 5.9 is used to account for these characteristics. Systems with higher ductility have higher R values.

With the above basic parameters available, the following design and analysis criteria can be determined. Seismic Design Category. The Seismic Design Category is based on the seismic group and the design spectral response acceleration coefficients, SDS and SD1, which will be explained later.

The Seismic Design Category for a structure can be determined in accordance, Seismic Design Categories are used to determine the permissible structural systems, the limitations on height and irregularity of the structural components that must be designed for seismic resistance and the types of lateral force analysis that must be performed.

Seismic Use Groups I and II structures located on sites with mapped maximum considered earthquake spectral response acceleration at 1-second period S1, equal to or greater than 0.75g, shall be assigned to Seismic Design Category E. Seismic Use Group III structures located on such sites shall be assigned to Seismic Design Category F. A structure assigned to Seismic Design Category E or F shall not be sited where there is the potential for an active fault to cause rupture of the ground surface at the structure. Building Irregularity. Building with irregular shapes, changes in mass from floor to floor, variable stiffness with height, and unusual setbacks do not perform well during earthquakes.

Thus, for each type of these irregularities, additional design requirements shall be followed to maintain seismic-resisting capacity. IBC 2000 requires that all buildings be classified as regular or irregular based on the plan and vertical configuration. See Tables 5.12 and 5.13 for classification and corresponding requirements. Design Requirements for Seismic Design Category A.

Structures assigned to Seismic Design Category A need only comply with the following:

- Structure shall be provided with a complete lateral-force-resisting system designed to resist the minimum lateral force, of 1% floor gravity load.The gravity load should include the total dead load and other loads listed below.

- In areas used for storage, a minimum of 25% of the reduced floor live load (floor live load in public garages and open parking structures need not be included)

- Where an allowance for partition load is included in the floor load design, the actual partition weight or a minimum weight of 10 psf of floor area (whichever is greater)

- Total operating weight of permanent equipment

- 20% of flat roof snow load where flat roof snow load exceeds 30 psf

- The direction of application of seismic forces used in design shall be that which will produce the most critical load effect in each component. The design seismic forces are permitted to be applied separately in each of two orthogonal directions and orthogonal effects are permitted to be neglected.

- The effect of this lateral force shall be taken as E in the load combinations. Special seismic load combinations that include Em need not to be considered.

The primary objective of earthquake resistant design is to prevent building collapse during earthquakes thus minimizing the risk of death or injury to people in or around those buildings. Because damaging earthquakes are rare, economics dictate that damage to buildings is expected and acceptable provided collapse is avoided.

Earthquake forces are generated by the inertia of buildings as they dynamically respond to ground motion. The dynamic nature of the response makes earthquake loadings markedly different from other building loads.

7. Define equivalent static loads analysis in progressive collapse. (Nov/Dec 2013)

Equivalent Static Analysis

The equivalent static analysis procedure is also essentially an elastic design technique, although some consideration of the post-elastic response enters into the selection of the determination of the lateral force coefficient (item 2 below). It is, however, simple to apply than the multi-model response method, with the implicit simplifying assumptions being arguably more consistent with other assumptions implicit elsewhere in the design procedure.

The equivalent static analysis procedure involves the following steps:

1. Estimate the first mode response period of the building from the design spectra.
2. Use the specific design response spectra to determine that the lateral base shear of the complete building is consistent with the level of post-elastic (ductility) response assumed.
3. Distribute the base shear between the various lumped mass levels usually based on an inverted triangular shear distribution of 90% of the base shear commonly, with 10% of the base shear being imposed at the top level to allow for higher mode effects.
4. Analyse the resulting structure under the assumed distribution of lateral forces and determine the member actions and loads.
5. Determine the overall structural response, particularly regarding the inter-storey drifts assessed for the elastically responding structure. (For the assessment of the post-elastic deformation, design standards typically magnify the elastic deformed shape by the structural ductility to determine the overall maximum deformation–typically at roof level. The introduction of a non-linear response profile to allow for local rotation at plastic hinge zones is often required when determining the inter-storey drifts.)

8. Mention some case study for building code approaches to progressive collapse.

- ✓ Most structural design standards in North America and in Western Europe have acknowledged the existence and potential consequences of abnormal loads and progressive collapse for some time.
- ✓ Most standards contain a statement of required structural performance, to the effect that local damage to the structure shall not have catastrophic consequences. In some codes, accidental loads are acknowledged explicitly (e.g., United Kingdom, Sweden, The Netherlands).

- ✓ Most recognize the desirability for continuity between structural elements, and several specify minimum tie forces to achieve continuity. Some specify the "notional removal" of an external load bearing element; others, a floor area or volume of damage that the remaining structure is required to bridge.
- ✓ The applicability of provisions varies from country to country – in some, they apply to practically all buildings, while in others only to certain forms of construction or buildings over a certain minimum height (typically 5 to 6 stories).
- ✓ ASCE 7/ANSI A58 first introduced a requirement for progressive collapse due to "local failure caused by severe overloads" in Section 1.3.1 of ANSI Standard A58.1-1972, the first edition following the 1968 Ronan Point collapse. No commentary or other guidance was provided. ANSI Standard A58.1-1982, Section 1.3, retitled General Structural Integrity, contained a more comprehensive performance statement, and referred to a greatly expanded commentary section and references for guidance.
- ✓ The 1988 and 1993 editions (now titled ASCE Standard 7) illustrated several structural system layouts that would lead to development of alternate load paths. Section 1.4 of ASCE 7-95 retained the performance requirement that a building be designed to sustain local damage, with the structural system as a whole remaining stable. However, the commentary was shortened, keeping the discussion of general design approaches to general structural integrity but eliminating the figures and other specific guidance. At the same time, a new Section 2.5 was added that required a check of strength and stability of structural systems under low-probability events, where required by the authority having jurisdiction (AHJ).
- ✓ The provisions in ASCE 7-98 and ASCE 7-02 are essentially the same as in the 1995 edition. The (non-mandatory) Commentary C2.5 recommends the following load combination for checking the ability of a damaged structure to maintain its overall stability for a short time following an abnormal load event:

  $(0.9 \text{ or } 1.2)\, D + (0.5\, L \text{ or } 0.2\, S) + 0.2\, W$ (1a)

in which D, L, W and S are specified dead, live, snow and wind loads determined according to Sections 3, 4, 6 and 7 of ASCE 7-02. This check suggests the notional removal of selected (presumably damaged) load-bearing elements at the discretion of the engineer without stipulating tolerable damage. If certain key elements in the structural system must be designed to withstand the effects of the accident (perhaps to allow the development of alternate load paths), they should be designed using the combination,

$(0.9 \text{ or } 1.2)\ D + A_k + (0.5\ L \text{ or } 0.2\ S)$ (1 b)

in which A_k is the postulated action due to the abnormal load. Normally, only the main load-bearing structure would be checked using these equations.

Building code officials in the United States have not been enthusiastic about provisions related to general structural integrity because they are difficult to cast in prescriptive code language and to enforce.

Most building codes in the United States have not contained such provisions. Whether the new paradigm of performance-based engineering and the related new initiatives will impact this resistance remains to be seen.

Eurocode 1 - The general design requirements in Section 2 of Eurocode 1 –Actions on Structures, Part 1 – Basis of Design (CEN 250 1994) state that a structures shall be "designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause."

The engineer is permitted to choose a design method that eliminates or reduces the hazard, uses a structural system that is insensitive to the hazard, ties the system together, or to design so that the system can tolerate accidental removal of an element. The design load combination used to demonstrate compliance using a specific "accidental" action, A_k, is specified as,

$D + A_k + \psi_1 Q_1 + \Sigma \psi_{2i} Q_i$ (2a)

in which ψ_1 and ψ_{2i} are companion action factors for "frequent" and "quasi-permanent" values of load, which depend on the load and are presented in a table. As an illustration for combinations of dead, live and snow load for light occupancies, we would have,

$D + A_k + 0.5\ L$ (2b)

$D + A_k + 0.2\ S + 0.3\ L$ (2c)

$D + A_k + 0.5W + 0.3\ L$ (2d)

Specific local resistance – In this approach, "hard spots" are designed in the structure, at areas that are believed to be prone to accidental loads (e.g., exterior columns at risk from vehicular collision or sabotage) or that may be required to develop alternate load paths. One such requirement that was proposed subsequent to Ronan Point was that key load-bearing elements surrounding residential compartments served with natural gas be designed to withstand a pressure of 34 kPa (720 psf).

This enormous pressure was based on a series of tests that measured explosion pressures in residential compartments. One unattractive feature of such an approach is that it provides resistance to only one hazard.

A second is that specifying such a load provides exactly the sort of information that one might require to defeat the design.

Specific abnormal loads seldom can be designed against economically; it is better to eliminate the hazard or control the consequence of local damage (Breen and Siess 1979).

9. How to design the progressive collapse against abnormal loading?

Progressive collapse has attracted the attention of engineers since the structural failure of Ronan Point apartments, London, UK, in 1968. Progressive collapse and robustness have become important issues in precast concrete cross wall constructions.

✓ Due to the importance of this type of collapse, a number of researchers have attempted to conduct studies to develop design guidelines that would reduce or eliminate the susceptibility of buildings to this form of failure. Today there are three methods to design against progressive collapse, which are:

- **Indirect method**. In this method, the overall robustness of the structure will be increased through tie reinforcements.
- **Specific local resistance method**. This method requires the designed elements to be able to resist a sudden accident which can lead to a removal of one member or more.
- **Alternative load path method**. DOD (2005) declares that this method can be used in two situations:

  a. When a vertical structure element can not provide the required tie strength; and

  b. For structures that require medium or high levels of protection.

There are still some limitations in the previous studies regarding progressive collapse. Summary of the knowledge gap is listed as follows:

- Limited number of studies for designing precast concrete cross wall constructions against progressive collapse.
- No systematic study has lead to a rational and justifiable method to design for such a failure. All of the current codes suggest ties as a preferable solution to that collapse. Most of them have been proved to be workable by the project evidence, and therefore may be deemed sufficient but not always necessary.
- Limited studies regarding ductility and in particular, its impact on progressive collapse.

10. How can we avoid the progressive collapse with regards to accidental load?

A structure is normally designed to respond properly, without damage, under normal load conditions. However, local and/or global damages cannot be avoided under the effect of an unexpected, but moderate degree of accidental overload. Usually, properly designed and constructed structures possesses a reasonable probability not to collapse catastrophically under such loads, depending on different factors:

- the type of loading (internal causes such as gas explosions – external causes such as impact by cars, etc.)
- the degree and the location of accidental loading in regard to the structure and its structural members
- the type of structural systems (skeletal, portal, wall framed structures), and the construction technology (insitu monolithic, precast, mixed precast/steel structures), spans between structural vertical members, etc.

Nevertheless, no structure can be expected to be totally resistant to actions arising from an unexpected extreme cause, but it should not be damaged to an extent that is disproportionate to the original cause, as shown in Figure 1, in which a single slab at one floor level failed during construction.

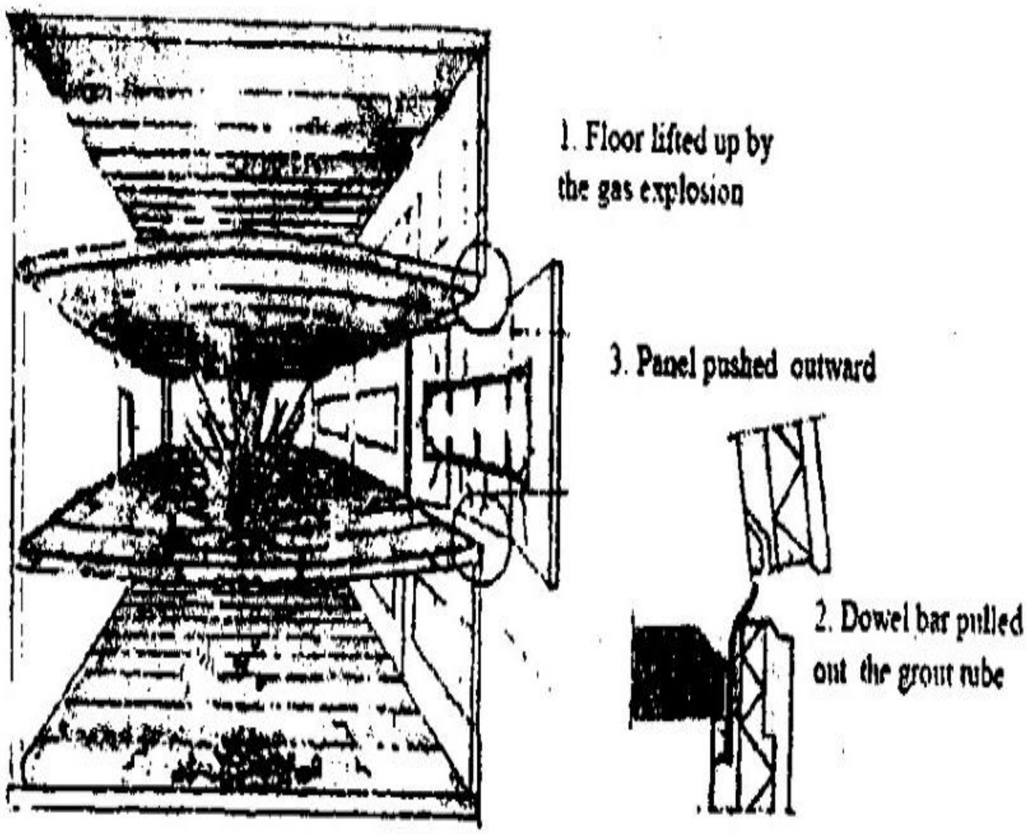


Fig. 2: Scenario of progressive collapse
after blowing-out of a load bearing façade panel due to gas explosion

Progressive collapse is a relatively rare event, as it requires both an accidental action to initiate the local damage and a structure that lacks adequate continuity, ductility, and redundancy to resist the spread of damage. It is technically very difficult and economically prohibitive to design buildings for absolute safety. However it is possible to construct buildings that afford an acceptable degree of safety with regard to accidental actions.