ROBUSTNESS VERSUS PROGRESSIVE COLLAPSE OF RC BUILDINGS

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Summary: *The paper point out the importance of robustness and the collapse resistant structure for reducing the progressive collapse of RC buildings. Terms and definitions used in connection with robustness and progressive collapse are given in concise form. The various ways of achieving the robustness, integrity and ductility of the structure are discussed. Short review of literature and some code provisions and recommendations, among them COST TU0601, for designing RC building structures for progressive collapse performance are given too.*

Keywords: *Accidental loads, local damage, progressive collapse, robustness, Codes*

1. INTRODUCTION

Contemporary building's structure due to optimization of design and less inherent continuity become more vulnerable to progressive collapse. In the design practice of structural engineering not much attention was paid to progressive collapse of an entire structure or a disproportionately large part of it. The term "progressive collapse" was first used in the UK following the partial collapse of a precast concrete wall at Roman Point, London in May, 1968. A gas explosion in a corner room in the eighteenth floor blew out one of the external walls, and because of inadequate structural continuity between the wall and floor elements, the removal of one wall element was sufficient to cause the total collapse of part of floor area per storey over the height of the entire building [4] and [10]. This building structure was of large panel concrete building. Generally, precast concrete structure is more inferior to structures of monolithic concrete buildings. Reason for that lay in sensitivity of joints and connections and orientation of precast floor planks [9]. According [5] accidental design situations refers to conditions applicable to the structure (local overloading) or to exposure, e.g. to fire, gas explosion, impact or the consequences of localised failure.

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2. TERMS AND DEFINITIONS IN CODES

Robustness-resistance to *progressive collapses* of buildings is the characteristic which defines the structure strength in term of integrity and redundancy. Progressive collapse is defined as situation where local failure of primary structural components leads to collapse adjoining members, which leads to additional chain collapse. Extend of total damage is disproportional to the initial damage. The term *disproportionate collapse* is used when the collapse is out of proportion to the event that triggers it, and always is a progressive collapse but a progressive collapse not always a disproportionate one [15].
The probability of a progressive collapse must be limited to a generally accepted value. Those value *P(F)* as a result of an abnormal event can be represented as a chain of partial probabilities [12] and [14]:

$$P(F)= P(F|DH) \cdot P(D|H) \cdot P(H) \tag{1}$$

where: P(H) denotes the probability of an abnormal event that threatens the structure or more generally a hazard H for the structure; *P(D|H)* is the probability of local damage *D* as a result of the event *H*; and *P(F|DH)* denotes the probability of the failure *F* of the structure as a result of local damage *D* by *H*.
In the expression (1) the first part represents robustness, second, element behaviour and third hazard. Product of first and second member is indicator of vulnerability and with hazard (third) can minimise.
Robustness is a term used to describe „the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause" [7].
Collapse resistance is a property that is influenced by both structural features as well as possible causes of initial failure. The term defined as insensitivity of a structure to accidental circumstances (low probability events).
Continuity refers to the continuous of connection of components as well as continues reinforcement of concrete components (Fig. 1). These properties improved integrity, redundancy local resistance and/or local resistance.
Ductility is the ability of the component or structural system to withstand large post-elastic deformations and increases the robustness of structure.
Damage tolerance is compatible with the term robustness, reefers to the ability of a structure to resist a continuous local deterioration due corrosion or similar.
Integrity related to requirements for continuity, ductility and redundancy. Enhanced integrity may mitigate progressive collapse. *Ties* contribute the ability of structure to redistribute or transfer loads along this load path based on large part on the interconnectivity between adjacent members.
Key element is a structural member upon which the stability of the remainder of the structure depends [7]. They should be designed for accidental loads, which are specified in several standards as 34kPa.
The loss of a major structural element typically results in load redistributions and member deflections. Structural *redundancy* refers to the multiple availability of load-carrying component of multiple load paths which can bear additional loads in the event

of failure. If one or more elements fail, the remaining structure is able to redistribute the loads and thus prevent a failure of the entire structure.
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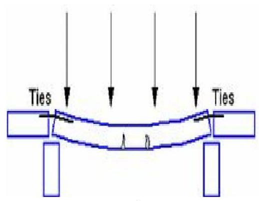
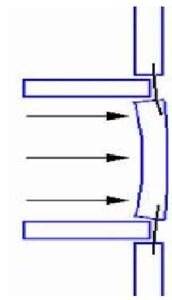


a)



b)

Figure 1. Tie to secure robustness: a) horizontal; b) vertical tie

Redundancy depends of geometry of structure and the properties of the individual load-carrying elements.
Vulnerability describes the sensitivity of a structure to damage events. The structure is vulnerable if small damage lead to disproportionate consequences.
Key elements are a structural member upon which the stability of the remainder of structure depends [7]. They should be designed for accidental loads, which are specified in several standards as 34kPa (Fig. 2a).
Definitions in EN are derived from ISO 2394, ISO 3898, ISO 8939 and ISO 8402. EN 1990 [5] *accidental action* means action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working (service) life. An accidental action can be expected in many cases to cause severe consequences unless appropriate measures are taken. Impact, snow, wind and seismic action may be variable *or accidental* actions, depending on the available information on statistical distributions. *Accidental design situation* involves exceptional conditions of the structure or its exposure, including fire, explosion, impact or local failure. Accidental design situations for the different consequences classes divided as followed [7]: CC1-consequences class 1: Low consequences of failure; CC2-consequences class 2: Medium consequences of failure; CC3-consequences class 1: High consequences of failure.
Hazard in EN 1990 to 1999 is treated an unusual and severe event, e.g. an abnormal action or environmental influence, insufficient strength or resistance, or excessive deviation from intended dimensions. A progressive collapse is a chain reaction which occurs after the damage or loss of load bearing capacity of a small part of a structure under incidental loads or in case when some bearing elements fail. According to robustness design Codes (BS) situations where damage to small areas of structure or failure of single elements may lead to collapse of major parts of the structure should be avoided [4]. All structures should be robust regardless on the likelihood of accidental loads. In [7], where designing for robustness is introduced, there are two design

situations to be considered: 1) designing against identified accidental actions, and 2) designing against unidentified actions (for disproportionate collapse or robustness).

3. ANALYSIS/VERIFICATION OF ROBUSTNESS

To society as a whole or to a company or institution responsible for a specific activity, the total damage due to a hazard is of prime interest. A variety of researches efforts in the past decades have attempted to quantify aspect of robustness such a redundancy and identify design principles that can improve robustness [1]. When a structure is designed to remain stable in damaged state via conventional analysis method the structure is bound to be extremely over dimensioned [16]. In [17] outline of the requirements and discussion of conventional and risk based methods and measures of structural robustness. The probability and consequence analysis related to the assessment of robustness usualy contains the statistical, fuzzy and fuzzy-statistical information on the basic variables and parameters. However, the progressive collapse of RC is initiated when one or more vertical bearing mambers are removed due to hazards. When any element fails, the remaining elements of the structure seek alternative load path to redistribute the load applied to it. As a result, other elements may fail causing failure mechanism [13]. The demand capacity ratio of RC twelve storey framed structure are evaluated as per US General services Administration guidelines. The linear static analysis is carried out using ETABS V9.7. But, analyse and enhance designs on sensitively to progressive collapse non-linear effects should be taken into account [16]. British Standard Code (BS 8110-1 1997 & BS 8110-2 1985) and [6] have similar guidelines. The layout of the building is checked to identify any key elements, the failure of which would cause the collapse of more than a limited portion close to the element in question. This key element design must be taken into consideration. Elements other than key elements are provided with vertical ties in accordance with the code provisions.
The redundancy of a structural system is related to its strength and shape, where particularly the degree of static indeterminacy (number of potential alternative load paths) is important. Besides, global design strategy based on classical requirements on sufficient ductility and tying of elements can be applied to achieve some degree of redundancy [8]. For conventional structures it should be possible to include all relevant collapse origins in the design.
In order to attain adequate robustness of the system one or more of the following strategies may be followed [8]:

- structural measures:

• limiting the amount of structural damage;
• designing the key structural components to withstand every possible load;

- non-structural measures (based on the general concept of avoiding actions (prevention) and reactions (protection), and mitigation of consequences):

• reducing the probability that the action occurs or reducing the action intensity
• reducing the effect of the action on the structure (protection);
• mitigating the consequences of failure.

Robustness by creating an alternative loading path: It should be made sure that in the case of an extreme event an alternative loading path can be mobilized around an area of local damage. Two *procedures for progressive collapse analysis* can be followed to verify the redundancy of a system: a refined procedure and a simplified procedure. According to the refined procedure, the occurrence and the effect of an accidental and/or exceptional action (impact, explosion, etc) are simulated for all possible action scenarios. The damage of the structural components is calculated and the stability of the remaining structure is assessed. Next, the consequences are estimated in terms of the number of casualties and economic losses. Various measures can be compared on the basis of economic criteria. The refined verification procedure is extremely complicated and does not work for unforeseeable hazards.

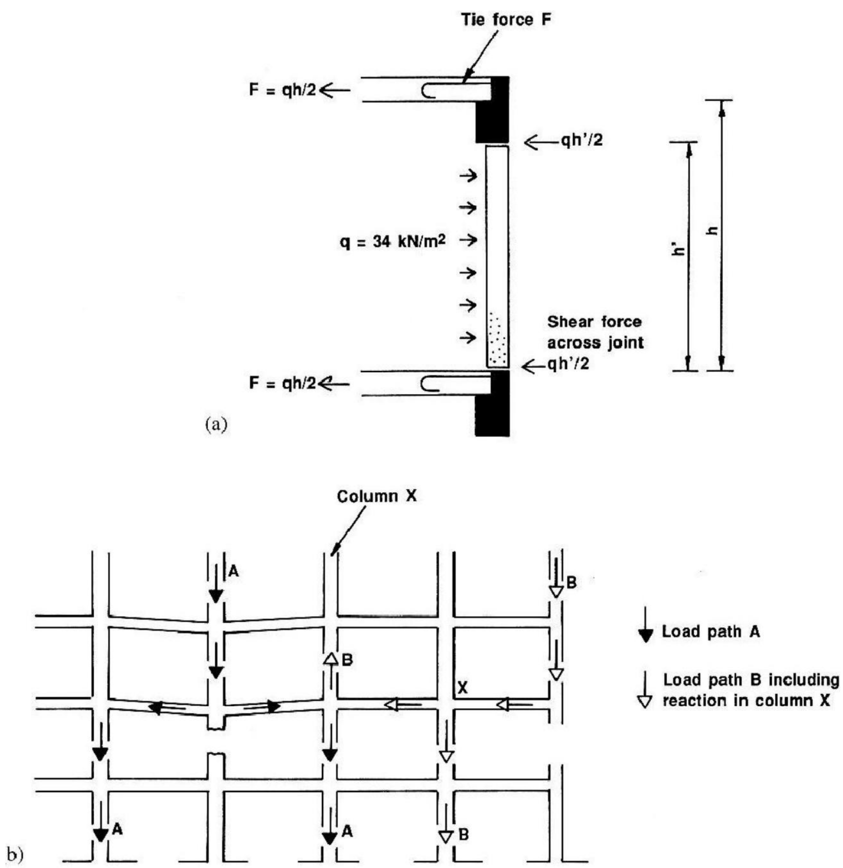


Figure 2. Altentaivemeans of protection against progressive collapse, a) protected member; b) alternative load paths, after [3]

According to the simplified approach, the situation is considered that any structural component that has significance for the bearing capacity of the structure can lose its bearing function. It is then verified if the remaining part of the structure can withstand the frequently occurring loads with defined target reliability for alternative load paths, for a relatively short period of time, necessary to mobilize the users of the structure and/or to carry out necessary repair or strengthening.

This target reliability for alternative load paths depends on the normal safety target for the structure, the period under consideration (hours, days or months) and the probability that the element under consideration is removed (by other causes then already considered in design).

Capacity design ensures a hierarchy of resistances of structural components and failure modes such that pre-emptive brittle failure modes are prevented and ductile ones promoted. To this end, brittle failure modes are verified for force action effects obtained not by analysis but from equilibrium, assuming that all relevant ductile components develop their force capacities. Ductile structural components are designed then for the plastic deformations induced in them by the design actions. Capacity design may also be used – in seismic design in particular – to prevent undesirable plastic mechanisms associated with limited global deformation capacity and enforce the intended one(s), involving only ductile structural components. In a building with a frame structural system a storey-sway mechanism can be prevented and a beam-sway one enforced, similar as in aseismic design.

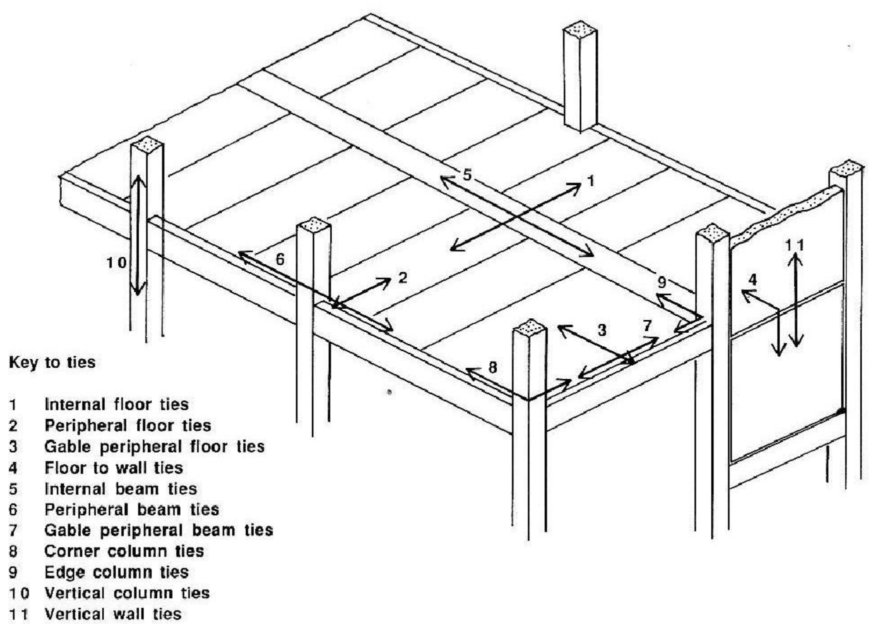


Figure 3. Types of ties in sceletal frames [3]

However, for sufficiently robust structures, failure consequences can be significantly reduced. Requirements and methods for the assessment of robustness in present codes are vague and seem to be insufficient for practical use. Therefore, the European research project COST Action TU0601 has been initiated to establish better understanding of the aspects related to robustness. Available robustness indices can be divided in three levels with increasing complexity:

1. Deterministic such as the deterministic reserve strength ratio (ISO 19902).
2. Reliability-based such as the redundancy index derived from failure probability of a damaged and intact structural system.

3. Risk-based proposed a definition of a risk-based index - ratio of the direct risk over the total (direct + indirect) risk. Consequences are divided into direct consequences (proportional to the initial damage) and indirect (disproportional) consequences.
Direct design the diversity and complexity of structures, aimed ensuring collapse resistance in a reliable, verifiable, and economical manner taking (assessment of the structure for specified performance objectives when subjected to specified hazard scenarios) into account. *Indirect design* aims at increasing the collapse resistance of a structure implicitly by incorporating approved design features without consideration of hazard scenarios and without demonstrating that performance objectives are met (providing tension ties, enabling catenary action, or ensuring ductility). The alternative methods are used to design for accidental damage: a) protected member; b) altentanive load paths; and c) use of ties (providing tying capacity).
It is necessary, for the prevention of progressive failure, to provide the continuity of tensile reinforcement in floor slabs and in bearing walls, as well as in external walls. Such vertical and horizontal continuity of reinforcement properly anchored at all floor slabs levels in the most important for general structural integrity and provides resistance to accidental loads [3] and [11].
The ties shall form part of a bridging system to span over the damaged area. Vertical ties should be continuous from the lowest to the highest level and be capable of carrying at least the design ultimate load applied by the floor immediately above that column/wall accidentally lost. Internal ties shall be at each floor and roof level in two directions approximately at right angles (Fig. 3).
They shall be anchored to the peripheral ties at each end (unless continuing as horizontal ties to columns or walls). The internal ties may, in whole or in part, be spread evenly in the slabs or may be grouped at or in beams, walls or other appropriate positions [3]. Joints are the most sensitive places.
For design joints and connections can use procedure described in [2]. Specific requirements related to position of ties in precast CS are given in BS 8110-Part 1, where are recommended two possibilities: a) ties could be embeded into in situ made concrete strips, or b) ties could be partialy embeded into in situ concrete and partly in the precast component [3].

4. FINAL REMARKS AND CONCLUSIONS

In spite of the fact that they are low frequency loads, a safety check of a building is required, especially of a multi-story building, against progressive collapse. A progressive collapse is a chain reaction which occurs after the damage or loss of load bearing capacity of a small part of a structure under incidental loads. Structural integrity and safety from progressive collapse require the application of an adequate design strategy through the choice of active and passive measures for controlling the appearance and spread of the damage, as well as for assessing the establishment of a potential load transfer system in the damaged structure [11].
The careful selection of a structural system and the careful processing of joint details are particularly important. In order to prevent progressive collapse it is necessary to provide

the greatest possible ductility and continuity of the structure. The way floor slabs, as well as the cores of the structure, are supported and assembled is important [4]. In order to prevent progressive collapse it is necessary to ensure maximum ductility and structural continuity (tying) and therefore the capability of a structure to develop alternative load transfer paths in case a vital element fails [3] and [10]. Insuring that elements can act together must provide tying system (Fig. 3) adequate continuity, ductility, and redundancy.

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РОБУСТНОСТ ВЕРСУС ПОРГРЕСИВНИ ЛОМ У АБ ЗГРАДАМА

Rezime: *У раду је наглашен значај робустности и отпорности конструкције за редукцију прогресивног лома АБ зграда. Сажето су дати термини и дефиниције везани за робусност и прогресивни лом. Različiti начини за постизање робусности, интегритета и дуктилности конструкције су наведени. Дат је кратак преглед литературе и неких одредби и препорука, међу којима и COST TU0601, za projektovanje AB konstrukcija zgrada.*

Кључне речи: *Абнормално оптерећење, локално оштећење, прогресивни лом, робустност, технички прописи*