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The Influence of Local Damage upon the Behavior of Reinforced Concrete Frame Structures

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Summary

Improvements in structural analysis and knowledge of materials over the last decades have led engineers to build structures that are structurally more efficient than in the past. This leads increasingly to extending the constituent materials to the limit of their operational envelope. The result is that modern structures don't have the strength reserve that was inherent in older structures engineered by empirical knowledge and instinct, and hence attention must be given for the way in which they will perform when subjected to abnormal loads.

From an analytical point of view, a progressive collapse is a structural failure that is initiated by localized structural damage and subsequently develops, as a chain reaction, into a failure that involves a major portion of the structural system. The residual structure is forced to seek alternative load paths in order to redistribute the load applied to it. As a result, other elements may fail causing further load redistribution. This process might continue until the structure can find equilibrium by finding stable alternative load paths.

The subject of this paper is the numerical analysis of reinforced concrete frame structures and the damage assessment of partially collapsed structures.

KEYWORDS: abnormal loads, robustness of structures, damage assessment, disproportionate failure, progressive collapse.

1. INTRODUCTION

Providing safety of a structure is one of the main aims of design. In traditional design it is achieved by designing structural components against specified limit states. However, as showed the Ronan Point collapse in UK in 1968, when a gas explosion in one of flats on the 18-th floor of a 22-storey residential building caused the failure of an entire section of the building [1], this approach is not sufficient. The approach does not exclude the risk of local damage to a structure due to accidental events (e.g., gas or bomb explosion, vehicle impact, gross errors in design, construction or utilization) that can occur during service life of the structure. While probability of occurrence of such events for ordinary structures is low [2], and therefore, they are not considered explicitly in design, their effect on structural safety becomes significant if the structure is not robust, that is when some local damage can trigger a chain reaction of failures causing collapse of the whole structure or of a major part of it, the so called progressive collapse.

The 1995 bombing of the Alfred P. Murrah Federal Building in Oklahoma City, the bombing of the US Embassies in Nairobi and Dar-Es-Salaam in 1998, and the collapse of the World Trade Center Towers in New York and a portion of the Pentagon in Washington due to the terrorist attack on September 11, 2001, drew renewed attention to the problem of reducing the risk of progressive collapse. Current efforts are aimed at the development of explicit design methods for reducing the potential of progressive collapse for new and existing structures [3].

It is recognized that different structures should possess different levels of robustness, which depend on their occupancy, type and size, exposure and other characteristics. Therefore, another new development is to categorize structures, which would require different levels of robustness, using a risk and consequence approach [4]. In this context, reliability analysis of undamaged and/or damaged structures is necessary, which would require probabilistic models of normal and accidental loads and materials properties under static and dynamic conditions [5].

2. ROBUSTNESS OF STRUCTURES

Robustness is a property, the description of which varies so much with context that it is difficult to put order into its manifold aspects, relationships and ramifications.

Robustness is the property of systems that enables them to survive unforeseen or unusual circumstances without undue damage or loss of function. It has become a requirement expressed in modern building codes, mostly without much advice as to how it can be achieved. Engineering has developed some approaches based on traditional practice as well as recent insight. However, knowledge about robustness remains scattered and ambiguous, making it difficult to apply to many specific cases. Robustness provides a measure of structural safety beyond traditional codified design rules.

The design of a system, being it natural or an artificial one, is typically oriented towards normal use, more precisely towards circumstances which must or can be anticipated to exist during the intended working life of the system. Limiting the design to this may however leave it vulnerable to the effects of events that were not included in the set of anticipated circumstances. These effects can be of very diverse character and may be related to the features that were anticipated in the design but for an unanticipated intensity, or that may not be of a description altogether foreign to the design circumstances [6].

Related to the life span of a building, robustness can represent the preserving of the integrity of the component elements properties, starting with the framing system (which also includes the infrastructure), closings, finishes and ending with the installations.

Robustness must not be understood as an over dimensioning of the elements but as the capacity of the system of adapting without damages to current actions and with minimum shortcomings to the extraordinary ones.

If we refer to the framing system of a building, the robustness has to provide it with the capacity of keeping its integrity to current actions and to not reach collapse in the case of extraordinary actions. When the extraordinary action is the seismic load, robustness must also include the dissipating capacity of the induced energy by ductility, through the capacity of the structural system to form plastic hinges in sensed zones even from the design phase. This means the capacity of the structure of accommodating to an unfavorable situation.

In order to say something rational and consistent on the property of robustness, some basic concepts must be described and clarified as far as possible – although a strict definition in the sense of a reduction onto other, well-known concepts may just be out of reach. One of the concepts foremost in need of this clarification relates to the issue of progressive collapse [6].

3. TYPICAL ASPECTS OF A ROBUSTNESS ASSESSMENT

A robustness assessment involves the following aspects:

- A *system* must be identified and clearly defined.
- *Specific system objectives* must be identified: system robustness relates to certain desirable system objectives (features, characteristics or properties).
- Specific *disturbances* such as hazards, internal or external influences, abnormal, deliberate or unexpected circumstances, or any other trigger events must be identified.
- *Robustness analysis:* this analysis focuses on the overall effect (consequences) of the specific disturbances (Step 3) as they affect the system objectives (Step 2).
- *Persistence:* any measures or indicators of robustness used to rank system robustness must be such that they assign high “marks” to:

- the persistence of the system objectives subject to the specific disturbances, or;
- a low and acceptable effect on the system objectives as a result of the disturbances.

The above process can be applied to any system (and its identified features) and to specific disturbances when none of these are subject to uncertainty. The robustness analyses are in fact entirely deterministic. However, in structural applications, the system, the system response, the cause-effect relationships, the hazards and the consequences are usually subject to considerable uncertainty. Therefore it is necessary to consider an additional element in the vulnerability assessment:

- *Risk*: the assessment of robustness must account for all uncertainties associated with system assumptions (Step 1), system objectives (Step 2), the occurrence of disturbances or hazards (Step 3), and model uncertainties involved in the system consequence analysis (Step 4) [7].

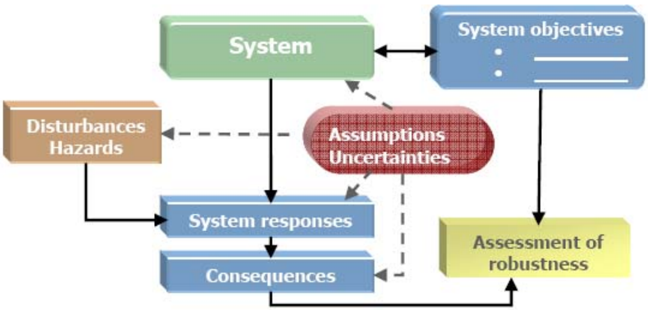


Figure 1. Schematic of the process of assessing robustness [7]

4. PROGRESSIVE COLLAPSE

A progressive collapse is a catastrophic partial or total structural failure that ensues from an event that causes local structural damage that cannot be absorbed by the inherent continuity and ductility of the structural system. The residual structure is forced to seek alternative load paths in order to redistribute the loads applied to it. As a result other elements may fail causing further load redistribution. Therefore, a local damage or failure initiates a chain reaction of failures that propagates vertically or horizontally through the structural system, leading to an extensive partial or total collapse. While virtually all structural collapses initiate from local as opposed to system-wide damage (earthquakes being a possible exception), it is generally agreed that the key feature distinguishing progressive collapse is that the resulting damage is disproportionate to the local damage caused by the initiating event. Such collapses can be initiated by many causes, including abnormal loads not normally considered in design (e.g., gas explosions, vehicular collisions, and sabotage), severe fires, extreme environmental effects that stress the building system well beyond the design envelope, human errors in design and construction, and misuse. All buildings are susceptible to progressive collapse in varying degrees [8, 9]. Continuous, highly redundant structures with ductility tend to absorb local damage well. Other systems, such as large panel or bearing wall systems, pre-cast concrete slabs or steel joist floors supported on masonry walls, and any building system that is well tied but lacks ductility are inherently more vulnerable because of the difficulties in providing continuity and ductility in such systems.

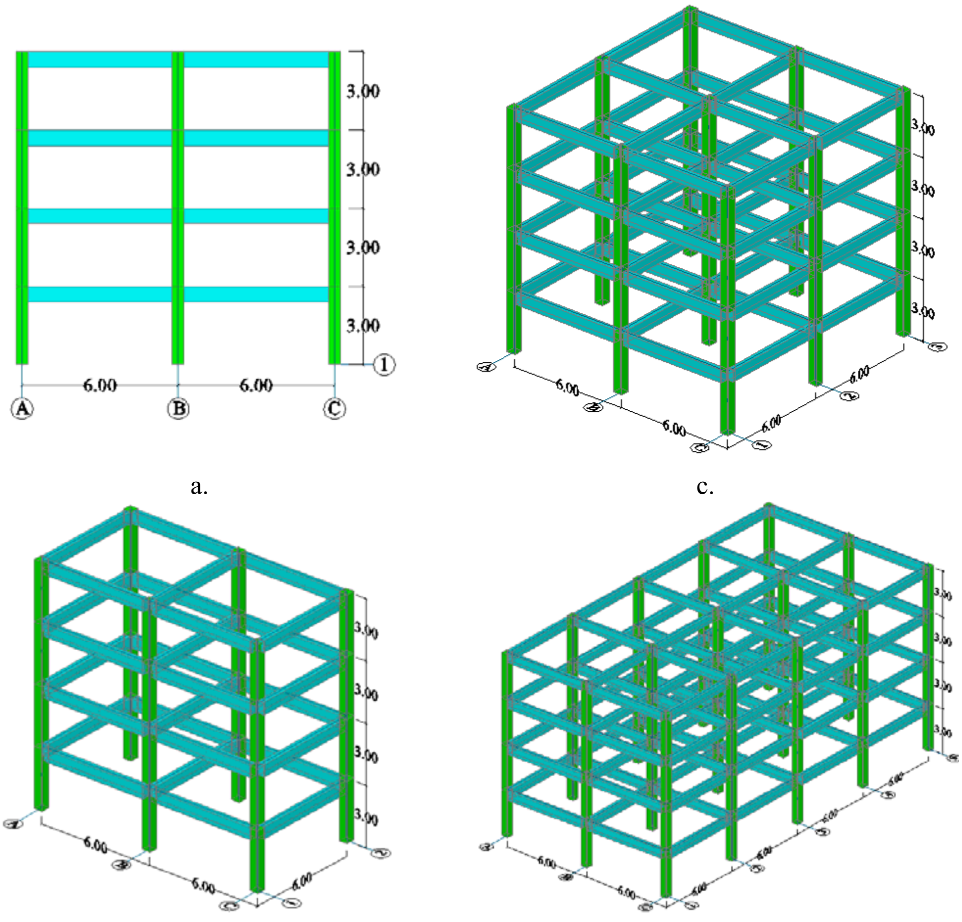
Specific design approaches to prevent progressive collapse as a result of abnormal loads have not been standardized. There are a number of reference papers on the subject and some studies leading to techniques that can be employed economically for certain construction types. However, building codes and standards that address the issue invariably treat general structural integrity and progressive collapse in qualitative rather than quantitative terms. This is due, in part, to the elusive nature of the definition of general structural integrity and the countless ways by which resistance to progressive collapse can be achieved. Moreover, the lack of quantitative provisions results from the difficulty that the engineering profession has encountered in defining specific events or initial conditions for which progressive collapse resistance should be considered, or the tolerable damage state of a building system that has restrained a progressive collapse successfully. Finally, there is the question of what is acceptable risk? No building system can be engineered and constructed to be absolutely risk-free in the presence of numerous sources of uncertainties that arise in the building process or from potential failure-initiating events. Building codes and standards provide tools for structural engineers to manage risk in the public interest. Of course, code provisions address the risks in building performance as the code and standard-writers have understood and confronted them at particular points in time. The renewed interest in abnormal loads, progressive collapse, and the associated hazards and risks is now taking place in a context that is very different from that historical understanding. Provisions for progressive collapse-resistant design have yet to be identified in terms of either performance level or risk [2].

5. CASE STUDY

In this first phase of the research activity there have been studied five different reinforced concrete frame structures, namely: a planar frame with two spans and four spatial frames having also two spans, but different number of bays (one bay, two bays, three bays and four bays). All the structures have four storeys above the ground level, each 3.00m high. The load bearing system of the structures consists of reinforced concrete columns and beams. The characteristic strength of the concrete is 20MPa. The load applied to the structures was a dead load of 10kN/m^2.

First, the planar frame structure has been modeled and the structural static analysis has been carried out using the Autodesk Robot Structural Analysis 2010 system. Then, starting from this model the spatial frame structures were modeled by adding progressively one bay.

In Figure 2 are shown the planar frame structure and three of the spatial frame structures with one bay, two bays and with four bays.



a. c.

b. d.

Figure 2. Studied frame structures. (a) Planar frame, (b) Spatial frame with one bay, (c) Spatial frame with two bays, (d) Spatial frame with four bays

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The aim of the analysis was to simulate the local damage of the central column from the first floor of the structures due to an impact loading and then to evaluate the damage state of the structures. It has to be noted that the central column from the first floor wasn't totally removed from the structures. Instead of this, the stiffness of the column was progressively reduced from 100% to 10%.

At each step of stiffness reduction the evolution of the bending moments of the beams along the axis no.1 and of the axial force in the central column from the intersection of the axis no.1 with "B" axis on each floor were recorded. The main interest was to evaluate the compound spatial effect between the initial transversal frame and the longitudinal structural elements progressively added to the structure.

The influence of the local damage from the first floor of the structure upon the load bearing elements from the upper floors was also evaluated. The values of the bending moments and of the axial forces were related to the values obtained at the first step of the analysis and the following diagrams were obtained.

In these diagrams M_A and M_B represent the values of the bending moment evaluated at the end sections of the beams and N_{max} represent the maximum value of the axial force at the bottom of the central columns from "B" axis. The numerical indexes refer to the considered storey and the index "c" refers to the value of the effort at the current step of the analysis.

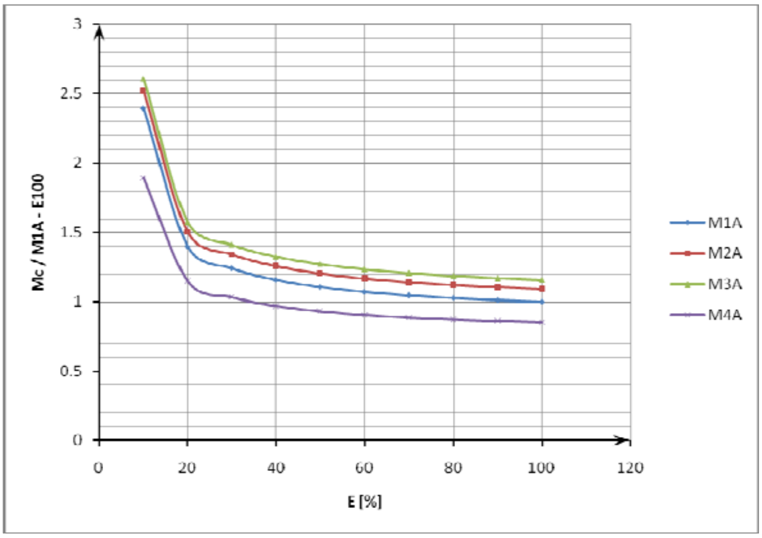

Figure 3. Bending moments M_A on each storey of the planar frame structure

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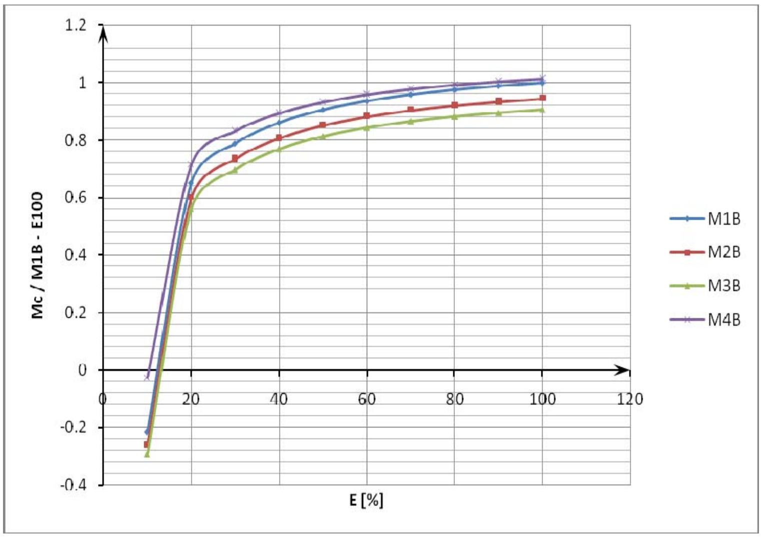

Figure 4. Bending moments M_B on each storey of the planar frame structure

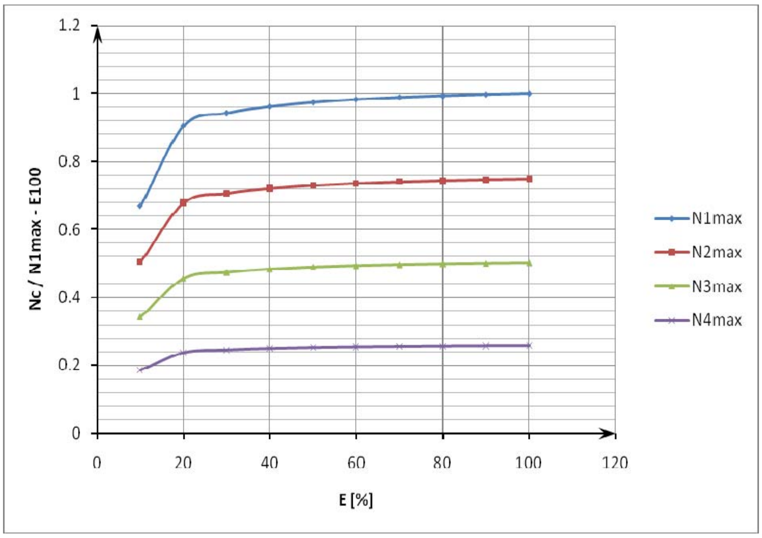

Figure 5. Axial force N_{max} on each storey of the planar frame structure

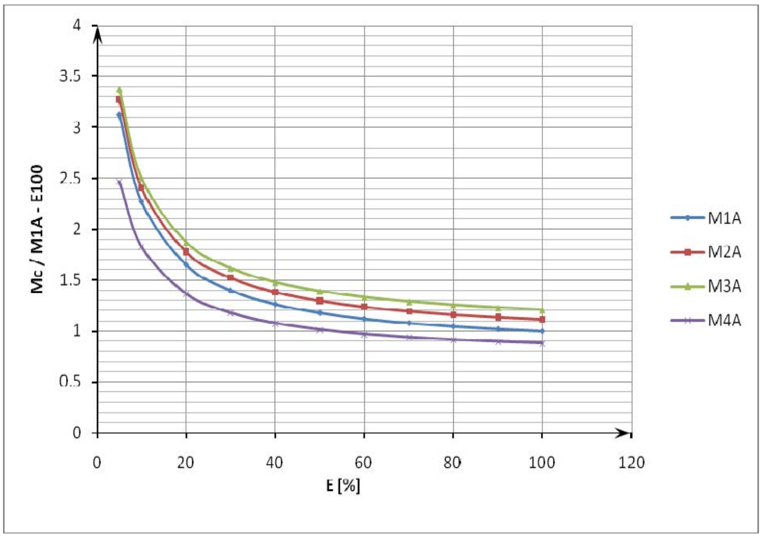

Figure 6. Bending moments M_A on each storey of the spatial frame structure with two bays

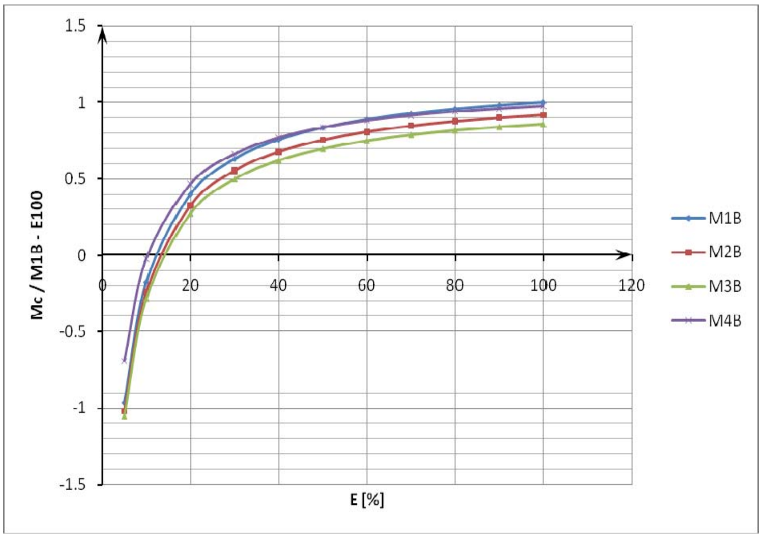

Figure 7. Bending moments M_B on each storey of the spatial frame structure with two bays

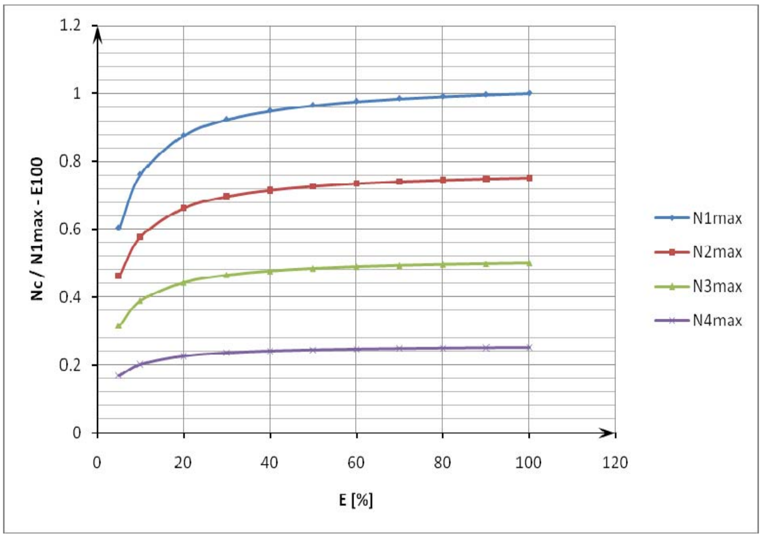

Figure 8. Axial force N_{max} on each storey of the spatial frame structure with two bays

As it can be seen from the previous diagrams, the structural elements from the upper floors are affected in the same proportion, the effort curves developed for each storey having almost the same shape. An inflection point in the evolution of the efforts appears in the case of planar frame structure when the stiffness of the central column is reduced at 30% and in the case of spatial frame structure it appears when the stiffness is reduced at 20%.

Both in the case of planar frame structure and in the case of spatial frame structures, when the stiffness of the central column is reduced to 10%, the absolute values of bending moment on the beams, M_A, increase suddenly and the bending moment, M_B, becomes positive.

In order to relieve more precisely the influence of the spatial effect upon the evolution of the efforts from the structure, the following diagrams have been drawn. The efforts evaluated in the case of planar frame structure were compared with those resulted in the case of spatial frame structures. As it can be seen from the following three figures, the behavior of the frame structure is improved when the longitudinal frames are added.

Based on these results, one may conclude that the analysis of the planar frame structures is not as precise and relevant for the real situation as the analysis of the spatial frame structures. Only the analysis of the planar frame structures has to be avoided and the compound effect of the spatial frame structures has to be taken into account.

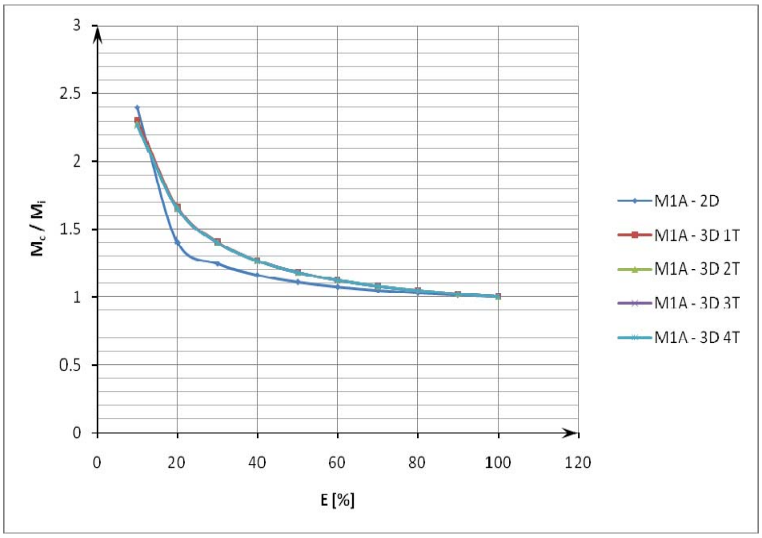

Figure 9. Bending moments (M_A) on the beams from the first floor

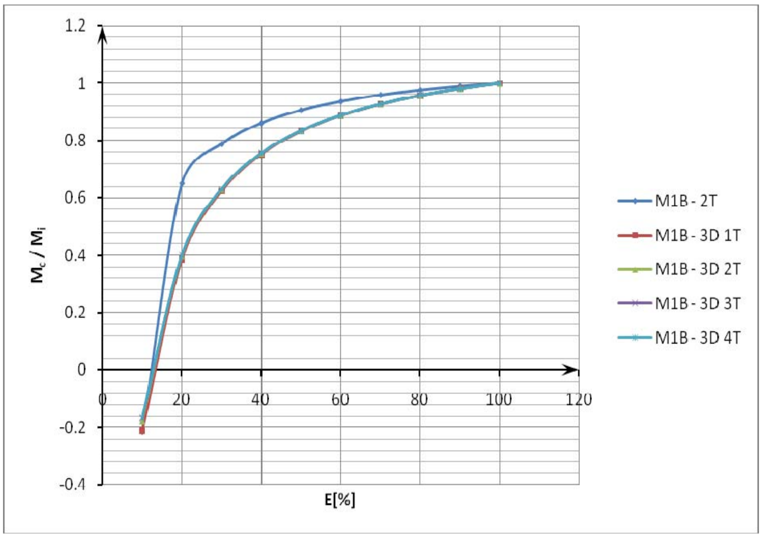

Figure 10. Bending moments (M_B) on the beams from the first floor

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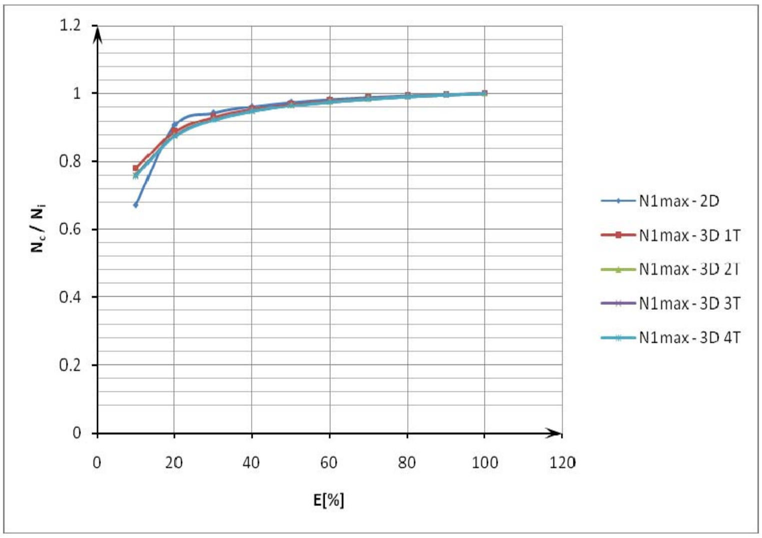

Figure 11. Axial force (N_{max}) in the columns from the first floor

6. CONCLUSIONS

The prediction of possible progressive collapse under specific conditions may provide very important information that could be used to control or prevent progressive collapse. It is now clear that abnormal loadings must be taken into account when designing structures. Abnormal load events could arise from a number of sources: gas explosion, confined dust or vapor conflagration, machine malfunction, high explosive effects, missile impact etc. However, to date, no adequate tools exist that can perform a progressive collapse analysis with acceptable reliability. Therefore, in the design phase, it is very important to predict the behavior of possible progressive collapse, as accurately as possible, for the various abnormal loads that should be considered.

One should be able to define a desired stable state of a partially damaged or partially collapsed structure for various abnormal loads and local damage combinations. Such collapsed cases and the damage evolution rate should be determined. Since the building after a partial collapse might be still exposed to a next phase of collapse, the residual capacity of a partially collapsed structure will determine its robustness, accordingly. A damaged or partially collapsed structure could be very dangerous without enough information about its expected behavior. The rapid prediction of future behavior, or the next phase of collapse, can increase the safety of both the occupants and rescue personnel.

Considering the results obtained from the present research work, it has to be mentioned the importance of spatial analysis of the structures. Compared to the behavior of the planar frame structure, the behavior of the spatial frame structures was significantly improved. But the number of bays didn't have such a significant influence since the evolution of the efforts in the axis no.1 is almost identical in the four studied cases of spatial frame structures.

It has to be noted that a stiffness reduction under 20% leads to the collapse of the structures.

For some specific types of buildings to which exists the risk of producing local damages it is necessary to assume some scenarios regarding the progressive collapse taking into consideration the necessary local measures for the preventing of global collapse.

The influence of local damage is diminished on the vertical direction with each new level added to the structure, the supplementary levels having a positive effect upon its behavior.

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