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# IMPROVING THE SAFETY OF ACCIDENTALLY DAMAGED REINFORCED CONCRETE COLUMNS THROUGH COMPOSITE ACTION

BY

**OANA-MIHAELA IONIŢĂ, *M. BUDESCU and N. ŢĂRANU**

**Abstract.** This paper provides initially an overview of some general issues associated with the robustness of structures. Firstly, a brief discussion related to the progressive collapse, from its basic definition, to the inherent difficulties of understanding, analysing and mitigating this phenomenon is presented. Attention is also drawn to the potential sources of abnormal loads that should be examined when designing for progressive collapse performance. In addition, some of the design standards that have been developed, and methods for designing to progressive collapse hazards, are discussed. Finally, a numerical analysis of a four storey reinforced concrete frame structure has been carried out and the results concerning the assessment of a progressively damaged structure are presented.

**Key words**: abnormal loads; progressive collapse; structural safety; robustness of structures; composite steel-concrete columns.

## 1. Introduction

One of the main aims of modern structural design is to provide safety of structures, *i.e.* to reduce the risk for the humans' life regardless of the type and nature of loading [1]. In traditional design this objective is achieved by designing structural components against specified limit states.

In some cases, when some local damage can trigger a chain reaction of failures causing the collapse of the whole structure or of a major part of it, the so called *progressive collapse* occurs [2]. One of the structural properties that can prevent the collapse of an entire structure when only parts of it are damaged or entirely destroyed is the *structural robustness*. As it can be easily understood, a robust structure is also a collapse resistant one.

The structural engineering community has tried to address the subject of progressive collapse from many perspectives, in an effort to develop a universal approach for the evaluation and the approaching of such an event.

The consequences of the progressive collapse can adequately be economically quantified, but more important, unfortunately, they can be sometimes quantified in lost lives. That is why it is of a great importance for structural engineers to develop methods for preventing and mitigating the progressive collapse of structures, enabling people to safely evacuate the affected buildings in the event of such a disaster [3].

## 2. Problem Statement

Progressive collapse is a catastrophic partial or total structural failure arising from an event that causes local damage that cannot be absorbed by the inherent continuity and ductility of the structural system [4]. The residual structure is forced to seek alternative load paths in order to redistribute the loads applied to it. As a result, the other elements may fail causing further load redistribution. This process might continue until the structure can find equilibrium by finding stable alternative load paths [5]. 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. 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 [6].

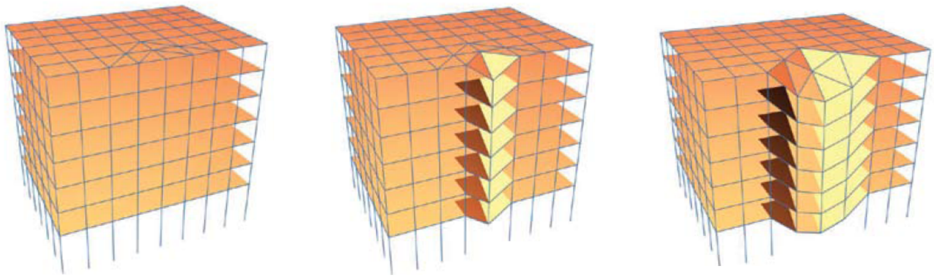
## 3. Methodology

Current efforts are aimed at the development of explicit design methods for reducing the potential of progressive collapse for new and existing structures, too [3].

The abnormal loading of structures is not limited to high-rise buildings only. It has to be taken into account when designing any kind of structures. Abnormal load events may arise from various sources: gas explosion, confined dust or vapour conflagration, machine malfunction, bombs, high explosive effects, vehicle, aircraft or missile impact, etc. [1].

A progressive collapse event is defined by ASCE 7-05 as "*the spread of an initial local failure from element to element, eventually resulting in the collapse of the entire structure or a disproportionately large part of it*" [7].

This definition of progressive collapse provides the first indication on how to approach a progressive collapse analysis. Certainly, the first step in evaluating the progressive collapse potential in a structure is to determine whether the initial target structural element, typically a column, has failed. In some cases, the target element is assumed to fail. The next step is to determine whether this failure has spread to adjacent elements, including beams, columns, and connections. Ultimately, the structural engineer must determine how much of the structure is expected to fail as a result of the structural member that was lost initially (Fig. 1) [3].



*a* – intact structure *b* – initial loss of a column and subsequent failures in the floors above *c* – failures propagating to the other bays

Fig. 1 – Phases of progressive collapse [3].

## 4. Evaluation Methods

Current design standards that address progressive collapse design issues include those of the *General Services Administration* (GSA) and the *Unified Facilities Criteria* (UFC) adopted by the *Department of Defense* (DoD). These standards provide two means of assessing progressive collapse in the design of new buildings or the evaluation of existing ones [3].

The *GSA Progressive Collapse Analysis and Design Guidelines* have adopted the *Alternate Path approach* to address progressive collapse issues. By adopting this methodology, the designer is required to systematically remove key gravity load carrying elements (columns or load-bearing walls) around the perimeter of the building and design the remaining structure to redistribute the loads without collapse. For a regular structure, a minimum of three separate analyses is required to adequately satisfy the criteria. A ground floor perimeter column, or a portion of the ground floor load-bearing wall, must be removed at the following three locations: middle of the long side of the building, middle of the short side of the building, and a corner location. For irregular structures, such as those containing reentrant corners, soft stories, closely spaced columns, or transfer girders, additional analyses may be required to adequately address all conditions [8].

The *Unified Facilities Criteria document, UFC 4-023-03: Design of Buildings to Resist Progressive Collapse* outlines four different levels of protection, ranging from *Very Low Level of Protection* (VLLOP) to *High Level of Protection* (HLOP), and the corresponding progressive collapse design requirements [9].

According to UFC document, in the case of buildings where the public access is restricted, the most critical locations for removing external columns are the following ones: near the middle of the short side, near the middle of the long side, and at the corner of the building, as shown in Fig. 2 [9].

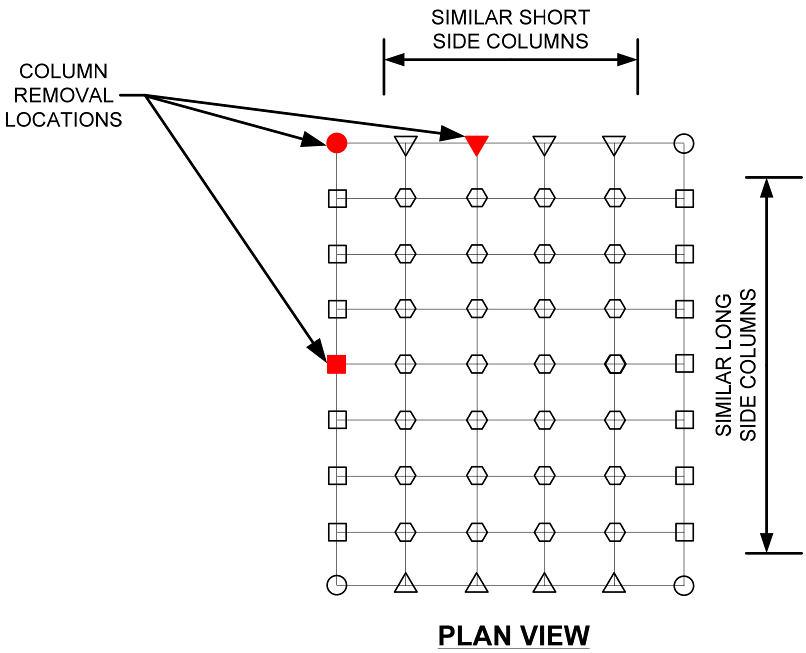



Fig. 2 – Locations of external column removal [9].

In the case of structures with underground parking or other areas of uncontrolled public access, the most critical locations for removing internal columns are the following ones: near the middle of the short side, near the middle of the long side and at the corner of the uncontrolled space, as shown in Fig. 3. The removed column extends from the floor of the underground parking area or uncontrolled public floor area to the next floor (*i.e.* one story height must be removed) [9].

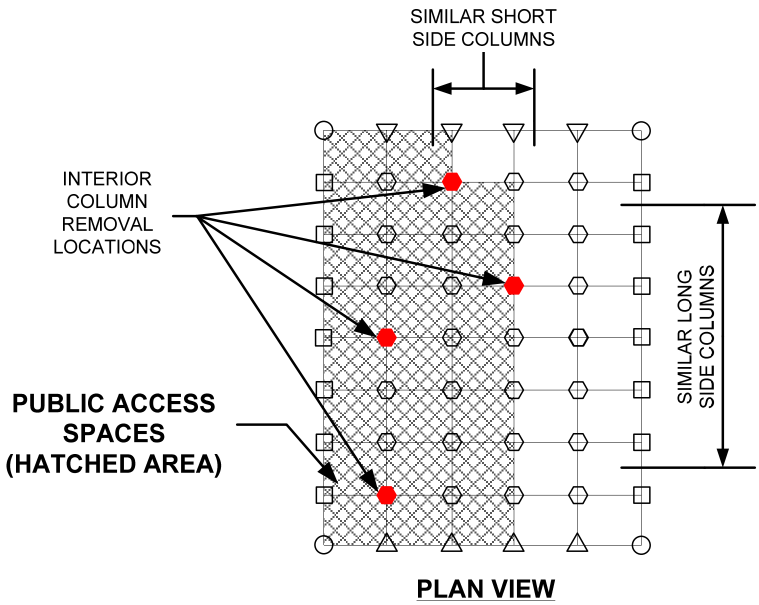
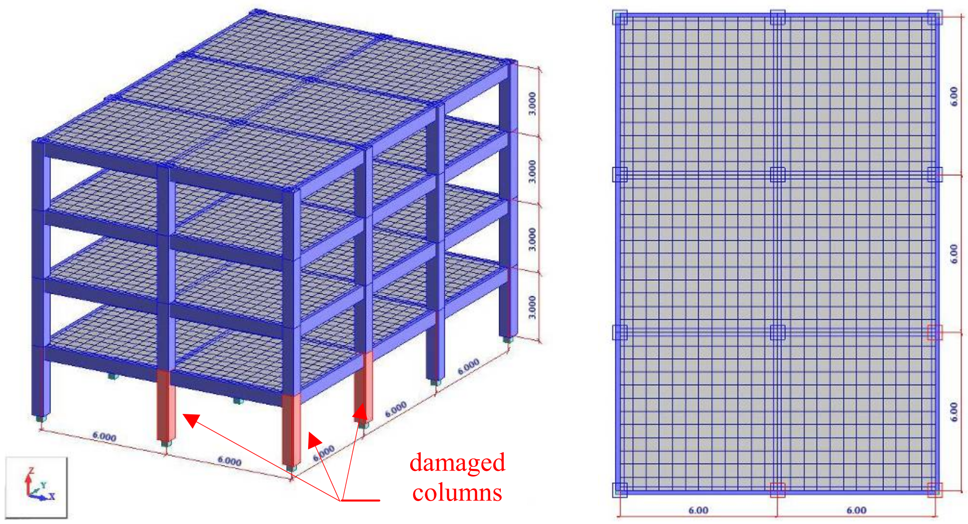



Fig. 3 – Locations of internal column removal [9].

## 5. Case Studies

A simple four storey reinforced concrete framing system (Fig. 4) was analysed in this study.




*a* – 3D view *b* – plan view

Fig. 4 – Structural configuration.

As it is shown in Fig. 4, the structure consists of two spans and three bays each of them of 6.00 m. The story height is 3.00 m. The perimeter and central columns are spaced at 6.00 m.

The load bearing system of the structure consists of reinforced concrete columns, beams and slabs. The structural members' properties are indicated in the Table 1.

**Table 1**
*Structural Members' Properties*

| Structural member | Width cm | Height cm | Concrete class |
|---|---|---|---|
| Columns | 55.00 | 55.00 | C25/30 |
| Beams | 30.00 | 60.00 | C25/30 |
| Slabs | – | 15.00 | C25/30 |

The structural modelling has been carried out using the Autodesk Robot Structural Analysis 2010 software.

For the purpose of this study, in addition to the permanent loads of the structure (*i.e.* dead loads (DL) of the structural elements), the following loading conditions have been assumed: the snow load (SN) at the terrace level of 2 kN/m$^2$ and a live load (LL) on each level of 2 kN/m$^2$. The following two load combinations have been considered: 1.35DL + 1.5LL + 1.05SN and 1.35DL + + 1.5SN + 1.05LL (according to Eurocode 1).

The aim of this analysis was to simulate the local damage of several ground floor perimeter columns from the structure due to an impact load and then to evaluate the damage state of the entire structure. It has to be noted that the columns have not been totally removed from the structure. Instead of this, the flexural stiffness of the columns was progressively reduced from 100% to 5% in order to simulate different degrees of damage.

Three different case scenarios have been considered. In these three case scenarios only one perimeter column situated in three different locations is progressively damaged: middle of the short side (A2), near the middle of the long side (B3) and corner of the building (A3). The location of the considered columns can also be observed in Fig. 5.

Normally, the occurrence of internal force members (*i.e.* bending moment for beams and axial force for columns) which do not exceed 30% in columns and 20% in beams can be redistributed to the adjacent elements.

Based on the performed analyses of the behavior of load-bearing elements it has been found out that for a stiffness damage ratio higher than 60% in columns, the development of internal force members may lead to a local damage or to the collapse of the framing system.

To avoid these undesirable consequences a composite steel–concrete column has been conceived. This column consists of a fully encased steel section, a wide I-beam HEA360 (further on denoted as RCS) with the steel grade S235, maintaining the same concrete class C25/30 (s. Fig. 5).

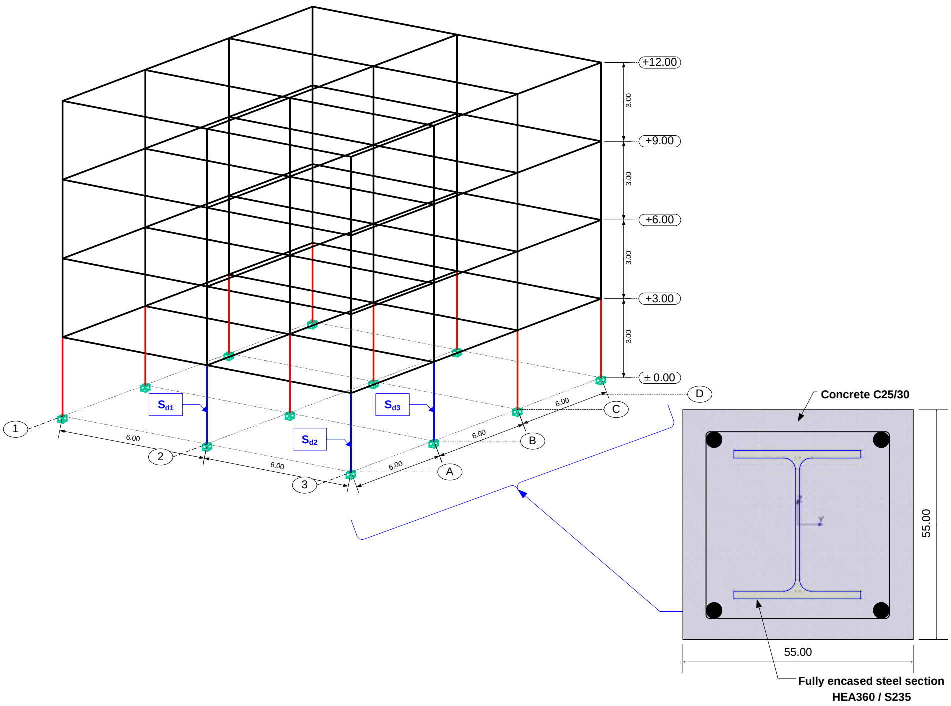



Fig. 5 – Location of the damaged columns and the composite steel–concrete section of the ground-floor columns.

This way, the five case scenarios that have been firstly analysed considering all the structural members made of reinforced concrete (further on denoted as RC) have then been studied considering that the ground floor columns were composite columns (RCS) as described above.

Using the normalized values of the internal force members a series of charts has been drawn. It was considered relevant to draw some comparative charts highlighting the efficiency of replacing the typical RC from the ground floor with RCS in those structures which are more possibly to be exposed to impact loading or any other kind of accidental loads. Some of these charts are presented bellow to illustrate the improved behaviour of the structure having ground floor composite columns compared to the structure made entirely from reinforced concrete members.

**Case Study no.1: Column A2 Progressively Damaged**

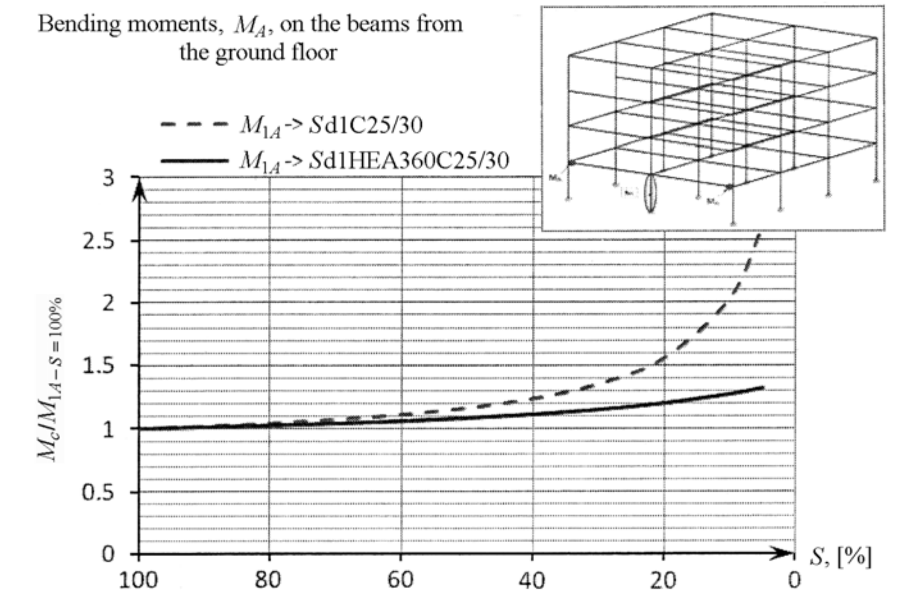



Fig. 6 *a* – Variation of the bending moment ratios for the column structures RC/RCS.

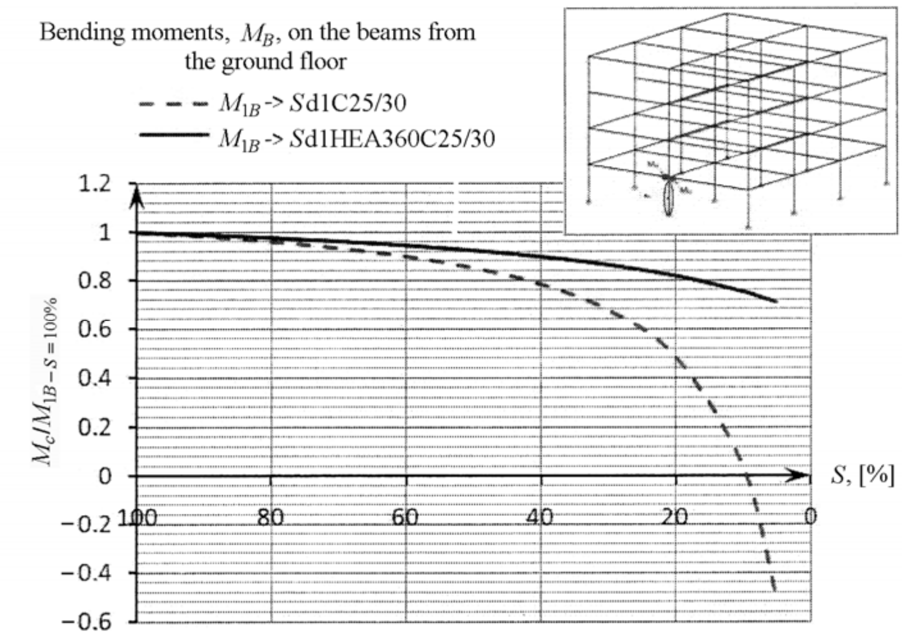



Fig. 6 *b* – Variation of the bending moment ratios for the column structures RC/RCS.

**Case Study no.2: Column A3 Progressively Damaged**

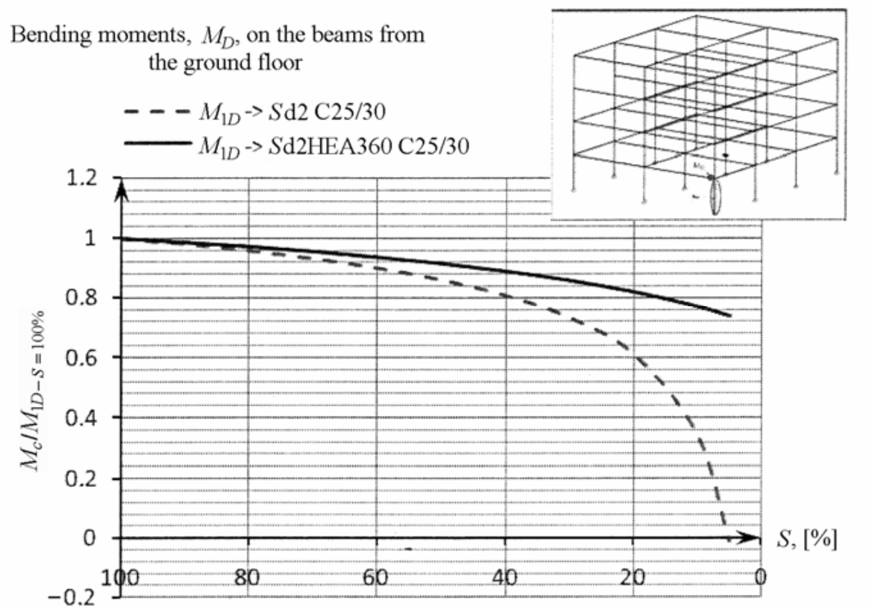



Fig. 7 *a* – Variation of the bending moment ratios for the column structures RC/RCS.

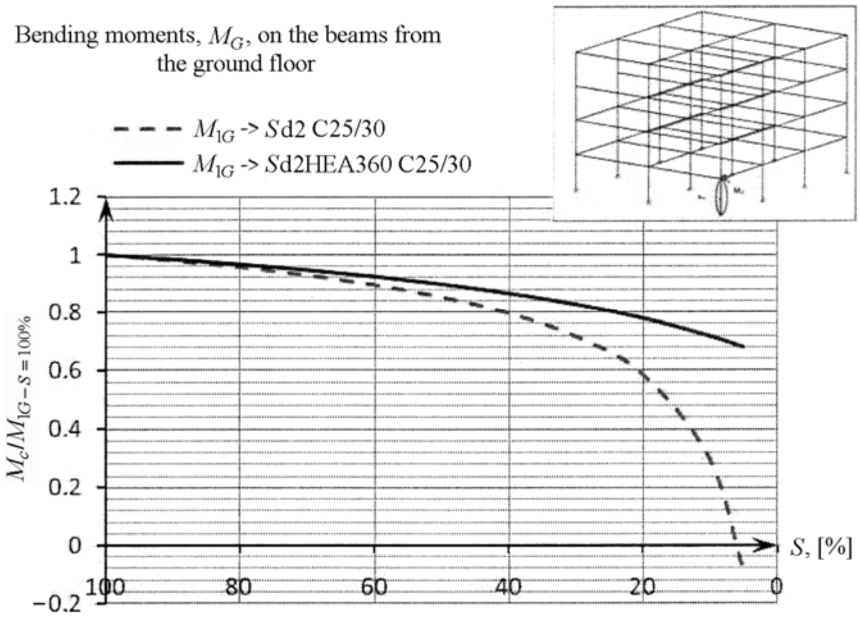



Fig. 7 *b* – Variation of the bending moment ratios for the column structures RC/RCS.

**Case Study no.3: Column B3 Progressively Damaged**

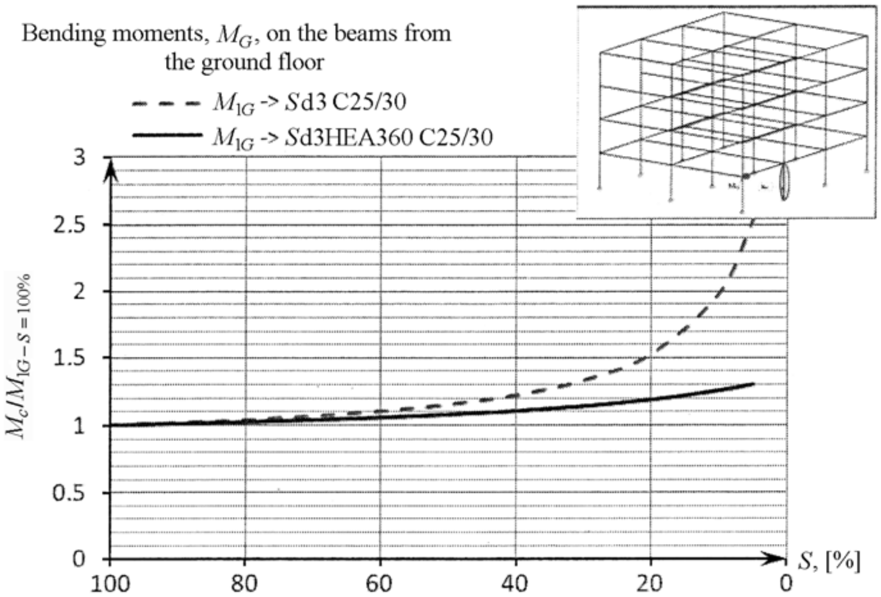



Fig. 8 *a* – Variation of the bending moment ratios for the column structures RC/RCS.

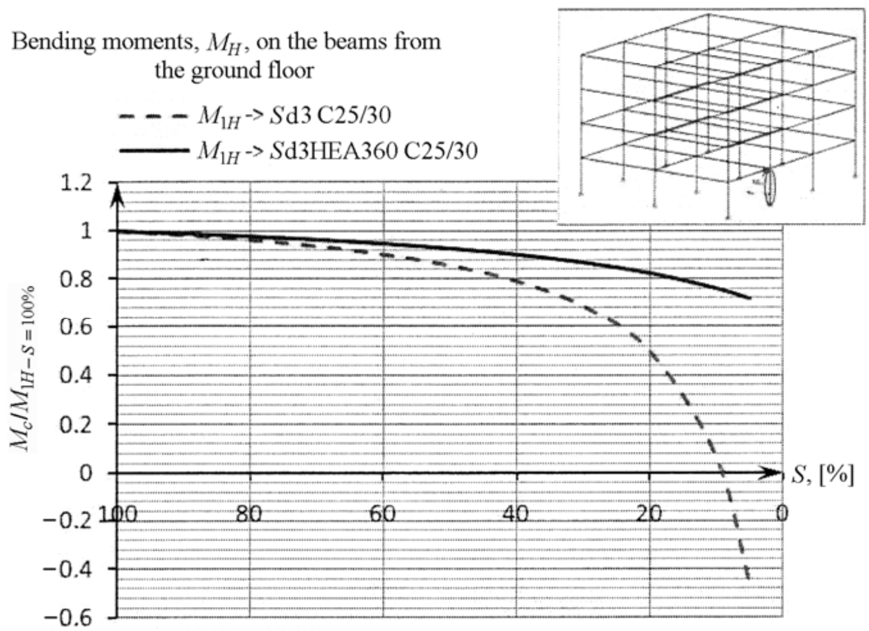



Fig. 8 *b* – Variation of the bending moment ratios for the column structures RC/RCS.

## 6. Conclusions

The prediction of possible progressive collapse under specific conditions may provide very important information that could be used to control or prevent this undesirable event. It is now obvious that abnormal loadings must be taken into account when designing structures exposed to unexpected loads.

Abnormal load events could arise from a number of sources: gas explosion, confined dust or vapour conflagration, machine malfunction, high explosive effects, vehicle impact, aircraft or missile impact, etc. However, up 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 still be exposed to a next critical phase, 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 and confidence of both the occupants and rescue personnel.

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

One efficient way of improving the safety of reinforced concrete structures may be the use of composite columns with fully encased steel sections at the ground level since this is more likely to be exposed to impact loading.

When the total flexural stiffness of the concrete section is degraded in case of reinforced concrete safety (RCS) columns the effect of the encased steel section is felt by increases of maximum 35% of the internal force members of the adjacent elements, avoiding, in this way, the progressive collapse.

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*„Gheorghe Asachi" Technical University of Iaşi,*
*Department of Civil and Industrial Engineering*
*e-mail*: ionita@yahoo.com
taranu@ce.tuiasi.ro
*and*
***** *Department of Structural Mechanics*

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## ÎMBUNĂTĂȚIREA PRIN ACȚIUNEA COMPOZITĂ A SIGURANȚEI STÂLPILOR DIN BETON ARMAT DETERIORAȚI ACCIDENTAL

(Rezumat)

Se oferă, inițial, o vedere de ansamblu asupra unor aspecte generale asociate cu robustețea structurală. Pentru început are loc o discuție succintă legată de problema colapsului progresiv pornind de la definiția sa de baza, până la dificultățile inerente întâmpinate în încercarea de a înțelege, analiza şi preîntâmpina acest fenomen. De asemenea se acordă atenție şi surselor potențiale de încărcări accidentale care ar trebui examinate în cadrul proiectării structurale împotriva colapsului progresiv. Adițional sunt discutate şi câteva dintre normativele care s-au elaborat, precum şi metodele de proiectare împotriva colapsului progresiv. În final s-a efectuat analiza numerică a unei structuri în cadre cu patru nivele şi sunt prezentate rezultatele cu privire la evaluarea stării de degradare a structurii care a fost progresiv degradată.