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**IMPROVING DESIGN METHODS AND CONDITIONS RELATED TO THE  
PROGRESSIVE COLLAPSE ACCORDING TO GSA AND DOD STANDARDS**

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**ABSTRACT**

Progressive collapse has been much considered in recent years that the countries like England and the United States have been leading in this field. In the United States of America, U.S. General Services Administration (GSA) and U.S. Department of Defense (DoD) have provided some standards, which have also been edited several times. In this paper, these cases are discussed. During these two decades, both the GSA and DoD had changes. In the meantime, the latest edition of GSA standard (related to the year 2013), has been accepted by removing all indirect approaches and accepting direct designing approach (load alternative path (AP)) that edited the related rules for coordination like DoD guidelines in 2009 (which was amended in 2013). The purpose of this study was to review the changes in GSA and DoD standards so that the reader of this paper understands an overview of the made changes and improvements. In addition, by increasing and development of finite element software, load alternative path (AP) method is slowly replacing other methods.

**Keywords: progressive collapse, conditions, standards, design methods, analysis methods**

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**INTRODUCTION:**

Progressive collapse is one of the events that cause damage for the entire structure or a large part of it by the localized collapse on a part of it. This issue is still being discussed in researches. Different methods have been suggested for designing a progressive collapse that these methods are divided into two general categories: A) Direct approach: In this method, the structure is evaluated directly through some analyses. B) Indirect approach: In this method, the structure will be resistance through observing some cases such as ductility, cohesion, and redundancy against progressive collapse. The structure designing is used on a limited basis against the progressive collapse, and it is observed only in buildings with high important coefficient that are exposed to the risk of fire, blast, or impact.

U.S. Department of Defense (DoD) has published UFC4-023-03 bylaw entitled "designing resistance buildings against the progressive collapse" for unified facilities criteria, and always updates it.

U.S. General Services Administration (GSA) is now responsible for the new development standard for the design of progressive collapse entitled "designing and analyzing guides for resistant buildings against the progressive collapse by alternative path

method". This guide is replaced with GSA2003 [6] entitled "designing and analyzing guides for the load alternative path for new governmental buildings and large modern projects". The purpose of this guide is securing this path by using security standards such as GSA and ISC [8], and reducing the difference between the design of GSA and DoD.

In recent years, the research results show that the test results of progressive collapse in buildings have a close result with the results of modeling these buildings in computer software. For this reason, the use of computer software is very common by the development of finite element science and numerical solution of different problems with linear and nonlinear methods. SAP2000 and PERFORM3D software are welcomed all over the world by having a great power in the nonlinear analysis, and they are used in the analysis of alternative path (AP) method. The most important problem in this regard is the selection of the analytical method and input materials specifications for the software, which should be considered a lot.

**Development of designing resistant buildings against the progressive collapse according to UFC 4-023-03 standards:**

**Overview of UFC 4-023-03 guide:**

U.S. Department of Defense (DoD) has started its work by developing UFC 4-023-03 entitled "analyzing and designing guide of resistant buildings against the progressive collapse with alternative path method". DoD had been expanded before it by the development of PC designing guide in response to the bombing of the Alfred P. Murrah Federal Building in Oklahoma City in 2001. However, after the terrorist attack on the World Trade Center in New York, two original copies of UFC4-023-03 were published in 2005 [3] and the next in 2009 [4] that the final amendments to it have been done in 2013.

Another aspect of the design philosophy of DoD progressive collapse the required level of progressive collapse based on the incident. Progressive collapse does not consider much ductility and resistance for predictable and unpredictable forces that have a low probability.

UFC4-023-03 standard is for designing resistant building against the progressive collapse when the threat is used on unknown or unexpected building. These unpredictable threats are like the impact of a means, blast pipeline and so on. Since, these threats are unspecified and unknown, a minimum initial force is required for the design that this force could occur through the elimination of

columns or wall cross in structures. It should be noted that this applied minimum force does not mean the parallel effects with the explosion load or the initial impact and if the real threat to be specified for training, the designer could act against this threat for building design by other DoD guides or similar guides.

Many concepts have been received from both UFC4-023-03 versions from the England bylaw after the collapse of Ronan Point apartment 1968 [9]. In general, this bylaw not only was effective on UFC, but also on all bylaws such as the United States, Canada, etc.

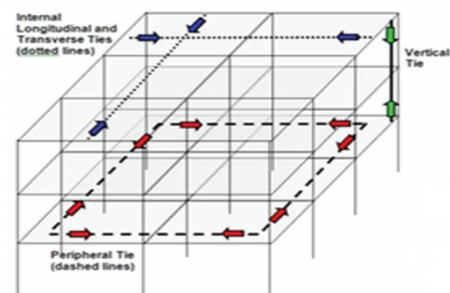
#### **The design methods of progressive collapse in UFC 4-023-03:**

UFC4-023-03 bylaw has two general methods of designing for the progressive collapse. A) Indirect design: In this method, the resistance is supplied against the design of the progressive collapse through the least resistance levels, association of members, and ductility. B) Direct design: In this method, the structure is analyzed and designed to resist the progressive collapse, in which an initial damage is caused to the structure. However, it should be noted that the horizontal member or bar above the removed member must maintain its continuity. The correct way of removing a

column is given in Figure 2. This action means the recommended design features to increase the ability to replay the load or expand the response mechanism of the structure to this damage. This method is called the load alternative path (AP).

Indirect design has been done generally through tie forces (TFs), in which the loads are transferred to other parts from the damaged part. As shown in Figure 1, these tie forces include vertical coils, longitudinal coils, transverse coils, and peripheral coils. In the past, the loading standard of America Society of Civil Engineers (ASCE7) had considered only some requirements for tie forces and it had refused to extend this issue. These requirements are: 1) suitable plan, 2) the continuity of power system, 3) walls performance, 4) direction change of openings at the bottom of slabs, 5) internal load bearing partitions, 6) uncertainties of structural system, 7) chain performance of floor slab, 8) ductile structural details, 9) considering the additional bars for the blast and reverse loads. As shown in Figure 1, TFs have been used to enhance cohesion, ductility and development of load alternative path. In the edition of UFC4-023-03 related to [3], TFs force has been given from the building bylaws. After Ronan Point disaster, these requirements got more forms because one of

the walls of the structure was removed due to lack of proper continuity in this event due to the low force by a blast to the structure. In UFC4-023-03 standard, TFs forces are imported in the floor and roof and they are tolerated by these members. These forces are not concentrated on beams, girder beams, and deep beams. Therefore, the floor system transfers the vertical loads to the healthy horizontal members (beams, girder beams, and deep beams) and finally, these members transfer the loads to the vertical members (columns or load bearing walls). The floor system is used as the secondary structural component to maintain the primary structural component from damage.



**Figure 1. TF requirements to UFC 4-023-03, 2013**  
In general, it should be said that TF method in UFC4-023-03 standard, edited in 2009 is in fact based on the direct design. TF value is obtained from the analysis of alternate path (AP) with an initial amount of damage in the structure (delete columns or wall sections). Thus, it is more correct to say that TFs

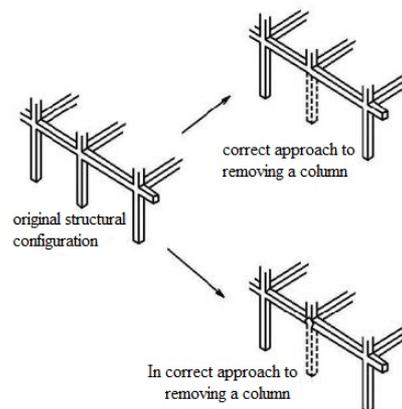
method is a subset of the direct design method.

Direct design methods include the explicit consideration of resistance against the progressive collapse during the design of the two methods. 1) The alternate path (AP) of load: it is the required ability of the bridge (I.e. if the vertical member or column be removed, the beam still maintains its continuity) due to loss of structural member (because of local damage). 2) Special local resistance (SLR) method: it requires enough resistance against the particular load or any threat in the building or a part of it. SLR method is used in United Kingdom bylaws [2] that this method was suggested with the name of enhanced local resistance (ELR) in UFC4-023-03 standard in 2009.

In the alternative path (AP) method, the structure should not exceed the limits of the damage and it should be sustained by removing the vertical load-bearing element. For this reason, removing the vertical load-bearing element (here, it is our desired column) must be in accordance with Figure 2. In UFC4-023-03 standard, the type of analysis is acceptable that include, linear static (LS), nonlinear static (NS) and nonlinear dynamic (ND). In this case, it should

be said that the linear static analysis method does not consider the effects of inertia and non-linear behavior and it has many irregular limitations. Non-linear static analysis only considered the non-linear effects of geometric and material, but it does not consider the effects of inertia. There is no limitation, such as irregularities and demand capacity ratio (DCR) to use it. Nonlinear dynamic analysis (ND) considers both mentioned effects, but this type of analysis is very sensitive to the input data and using this method and interpretation of the relevant outputs of software require experience and expertise. These three analysis methods were re-evaluated and modified by AP method the related conditions. Finally, ASCE41-06 [1] bylaw entitled "seismic retrofitting of existing buildings" in UFC4-023-03 standard was applied considering the seismic design criteria.

Another most important change in this guide that has been made in recent years was the changes related to load increase factor. This factor has been provided in the form of two tables to increase the load factor for load increase factors for linear static analysis and load increase factors for nonlinear analysis.



**Figure 2. Bending bridge for the alternative path**

One of the unique advantages of explicit ASCE41-06 is expressing the requirements and recommendations for different building types, and it is used for a variety of materials. Another advantage of this bylaw is the modeling parameters and conditions that can be scaled on functional levels (life safety and the verge of collapse). This guide is developed for force-controlled actions, deformation-controlled actions, structural and non-structural members, lower bound resistance, specifications of materials and components. ASCE41-06 bylaw is a comprehensive method to design structures under dynamic loads with large deformation. While ASCE41-06 bylaw has been provided for seismic loads, which are applied immediately and horizontally. However, it can be used in some parts that loads are applied vertically and permanently for designing a progressive collapse. On one

hand, all resistance reduction factors are considered as a unit in all relationships in ASCE41-06 bylaw. While, these factors in UFC4-023-03 guide are smaller than unity (these values can be derived, for example, in RC structures from ACI318-11 standard). With some modifications in the conditions of this bylaw in linear and nonlinear methods, these criteria were included in the UFC4-023-03 standard in 2009. For example, Chapters 5 to 8 of ASCE41-06 bylaw can be mentioned (relating to the acceptance criteria of reinforced concrete, steel, etc. structures).

#### **Amendments to the UFC 4-023-03 bylaw:**

Two years after the release of UFC 4-023-03 in 2009, DoD has applied important changes to improve this bylaw [5], including:

- ✓ Adding cold-rolled steel: An example of cold rolled steel is attached in Appendix G, in which the plan and height are the same as the

- example of wooden building in Appendix F. In this example, the AP method has been used with manual calculations used to remove the wall.
- ✓ Modifying applied loads: In load and resistance factor design LRFD, the combination of down loads has been modified due to two aspects. The first reason is that this combination rarely affects the design of buildings, and the second reason is that in many cases, it causes confusion and increases their calculation of structures. For this reason, the first change in the combination of this load  $G = (0.9 \text{ or } 1/2) D + (0.5L \text{ or } 0.2S)$  is removing the factor of 0.9 from gravity load and the second change is removing the required lateral factor in every four sides of the building.
  - ✓ Clarifying the definition of controlled public access: According to DoD 4-010-01 standard entitles "minimum standards for terrorist attacks", controlled public access is defined as an electronic tool available to control and mechanical locks of exterior doors. This in turn can increase the level of access to the important places.
  - ✓ Another most important change that has been applied in this guide is the changes related to load increase factor. This factor has been provided in the form of two tables static increase factor and dynamic increase factor.
  - ✓ Modifying the controls related to non-structural components examples for linear static method (LS): In LS method, non-structural components need to be controlled by criteria for AP designing process. This control can be done using several methods that the available examples have been fully processed in the Appendix for explanations.
  - ✓ Re-proposing the ELR conditions in LRFD design format: If the shear strength of columns is greater than bending strength, ELR requirements are similar to all parts, but designing LRFD conditions related to ELR is rewritten.

**The cost of using the UFC4-023-03 standard:**

The costs of applying the requirements relating to the design of progressive collapse in real structures that have been built according to UFC4-023-03 standards in 2009

were evaluated. The estimated cost for four examples is given in Appendix D to G.

#### Appendix D: An example of reinforced concrete structure

Figure 3 shows the plan related to a building whose area is 13,900 square meters. This example is related to a seven-story commercial building with moment frame that TFs and ELR methods have been used to design it. The corner columns and the penultimate of the ground have been used. It should be noted that this structure has used

UFC4-023-03 guide, and its cost has been calculated based on dollar. The costs of this structure have been estimated for the structural frame and the whole structure. Table 1 has estimated the base and the costs associated with work and additional materials to adhere to TFs and ELR. The total cost increase of the building is 1.38% that the acceptance of this cost should not be considered high for structures with high importance.

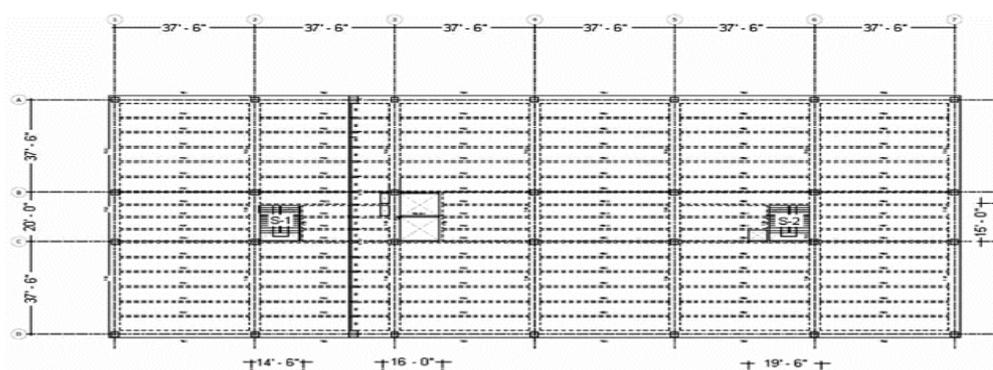


Figure 3: The plan of a reinforced concrete building (from DoD 2013)

Table 1: The costs of reinforced concrete buildings

Structure only or entire building	Baseline cost (dollars)	Baseline plus TF and ELR	
		Cost (dollars)	Increase (%)
Structural frame	6,796,812	7,429,580	9
Entire building	46,348,152	46,980,919	1

#### Appendix E: Example of steel structures

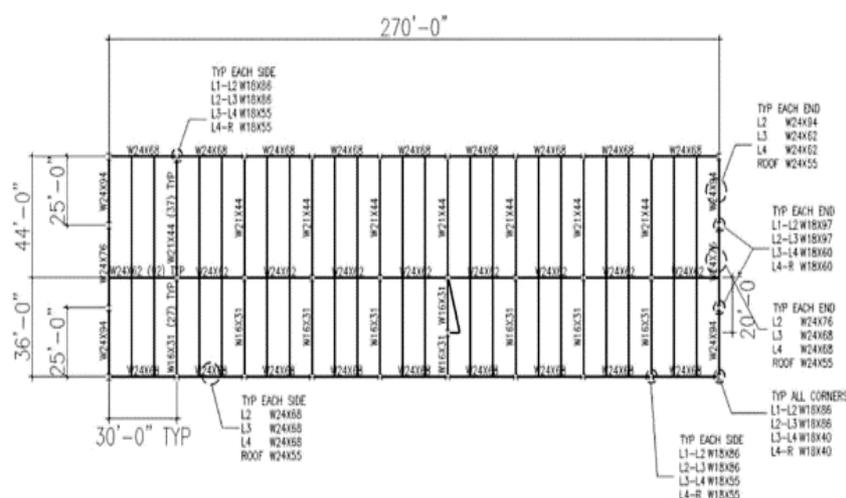
Figure 4 shows the plan of the building whose area is 8027 square meters. This example is related to a 4-storey steel building with moment frame, in which AP and ELR

are used to design the progressive collapse in the columns around the ground. 1) AP is only used to remove the outer column. 2) AP is used to remove the outer and inner columns that all results have been shown in Table 2. It

is noteworthy that, LS method is more conservative than ND and ND method is more accurate than LS method.

Since, wooden and, cold-rolled steel buildings are not applicable in Iran;

therefore, we refused to explain about these systems in Annex F and G.



DoD design methods. The focus of this guide is reducing progressive collapse due to blast threats on the ground and public areas with high risk. In this guide, progressive collapse reduction can be strengthened to prevent the destruction of the bearing components regarding the protection level of the building (FSL).

**Application by having a security level:**

The most important and basic case in GSA guide is classifying the building according to the facility security levels (FSL), in which we need to determine FSL according to the specifications of the building, the number of residents, or the number of floors. Then, the design of each level is determined according to the specified security facilities. Initially, we define the facility security level. "Determining the security level for federal facilities" bylaw determines the conditions and requirements for FSL, in which the classification is done based on multi-parametric analysis of security, which includes a goal.

FSL application normally includes the following cases:

Facility security levels of I and II: In these two security levels, the number of residents and the level of risk associated with this type of equipment is low and the progressive collapse design it is not necessary regardless of the number of its floors.

Facility security levels of III and IV: this guide is necessary for buildings with four or more floors than the top of the lowest point of balance. It should also be noted that parking lots and the floors with no residents are not considered as a floor. In these security levels, AP and additional redundancy should be used that AP method is run based on removing the vertical bearing component according to the conditions of DoD bylaw.

Facility security level of V: this bylaw should be run for all buildings with the security level of 5, regardless of the number of floors. At this level, AP method should be run based on removing the vertical bearing component in the desired site. In addition, the design process of added redundancy is not necessary at this level.

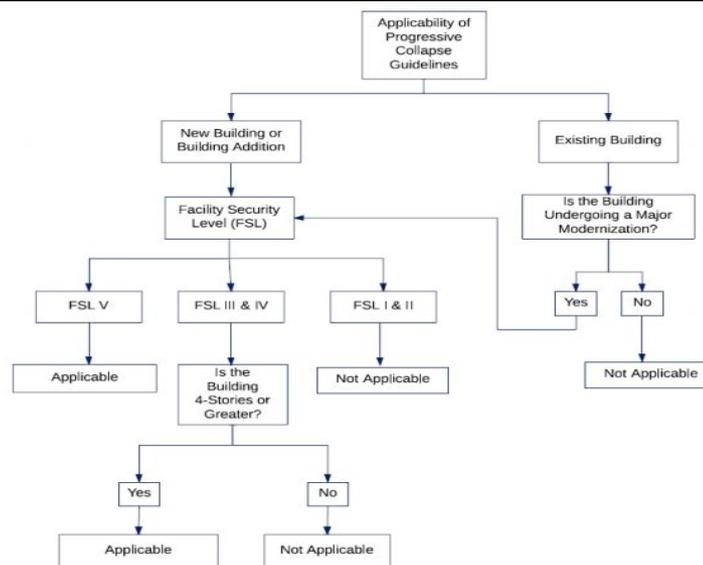


Figure 5: The flowchart related to the design of progressive collapse in accordance with the GSA 2013

### AP method and requirements of redundancy:

In the conventional mode, methods, ranges, and conditions, accepted by UFC4-023-03 were identical for LS, NLS, and NLD with the new bylaw of GSA.

The requirements of redundancy should also be added. The purpose of this work is guiding designers to prevent the progressive collapse in some areas of the floor. However, the local systems in the floors can answer the acceptance conditions related to AP method in removing the column or wall on the ground, but finally, they show an unbalanced and unstable system. The requirements of added redundancy have been shown in Figure 6, which include the following cases:

- Vertical load redistribution systems: Load redistribution systems should

be considered around the structure for the mentioned design requirements. In general, load redistribution systems are a structural system that has ability to redistribute loads to adjacent structural elements in the absence of load-bearing columns or walls.

- Requirements relating to removing place in the height: the maximum interval of floors for removing the bearing elements is equal to three floors, which is shown in Figure 6.
- Requirements related to resistance: Design resistance changes for removing place of each column or wall peripheral the ground should be  $\pm 30\%$  of the average design resistance for each load redistribution

system, which have been extended until the end of the building. It should also be noted that no scenario is needed to remove the wall or column in this work.

$$\left| \frac{Q_{R1} - \overline{Q_R}}{Q_R} \right| \leq 0.3$$

- For this reason, the requirements relating to flexural stiffness must be met. Here, these requirements are

ignored for brevity because all of its issues are related to resistance requirements.

- Column requirements: the columns between load redistribution systems must be designed as the collector and receive redistributed loads from other systems. Patch at the collector components must be designed to withstand tensile loads.

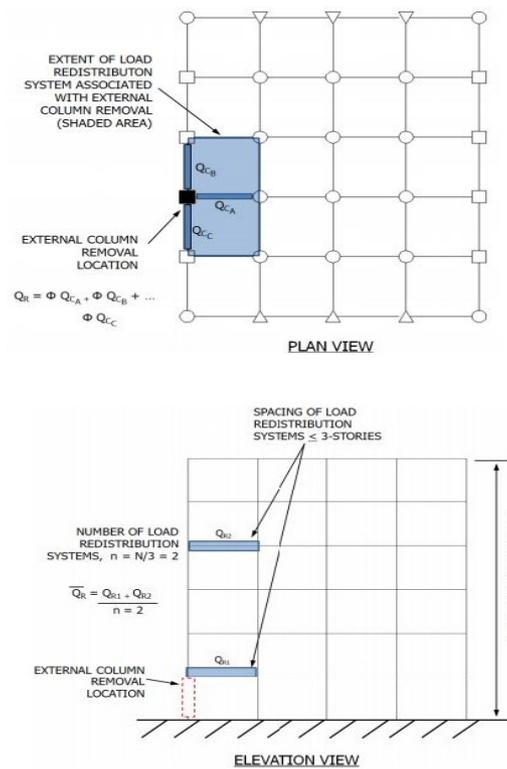


Figure 6: The plan and the height of buildings to show load redistribution systems

**Continuing the standards development and research on the progressive collapse:**

Development of designing methods for structures has been widely discussed in the

recent literature based on their performance. Structural Engineers Association of England has published a number of papers related to risk estimation of structure and functional

design of progressive collapse based on their risk estimation.

Structural Engineers Institute of the United States (SEI) recently has formed Disproportionate Collapse Standard Committee (DCSC), which aims to develop a consensus for designing structures resistant to disproportionate progressive collapse. The first Committee related to it was formed in the structure Congress of Pittsburgh in 2013, with more than 50 members. Currently, subcommittees are formed for each 9 chapters of the bylaw and they hope to finish the DCSC standards until the next five years.

#### **CONCLUSION:**

The purpose of this paper was to get familiar with various types of new and updated standards in the field of progressive collapse. As we have seen in this study, all standards and bylaws tend in one direction. In the not too distant future, we will witness the prosperity of these bylaws. The most important and the most reliable method for designing a progressive collapse according to the progress of structure engineering science during the past few decades in the field of linear and non-linear computer calculations is load alternative path (AP) method. Iran has significant advances in the field of linear and non-linear computer calculations for structures. These advances were achieved by

software such as SAP, which is one of the most comprehensive software for progressive collapse analysis and PERFORM3D, which can be useful in some cases, ABAQUS, an OPENSEES, which is mostly for researching. Therefore, it can be said that the load alternate path method must be used in Iran like in developed countries for very important buildings, which are given in the context of the twenty-first national building regulations of Iran entitled as buildings with a special degree of importance.

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