PROGRESSIVE COLLAPSE OF TALL BUILDINGS - REGULAR & IRREGULAR STRUCTURE

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Abstract: *The prime concern of the structural engineering fraternity across the globe is the safety of human lives. The community of structural engineer is well aware about the consequences of accidental and rare events like Earthquake, Tsunamis, Fire, Tornado and Blast. Therefore, lot of research is being done in all parts of the world to design the structure that can minimize or eliminate causalities in such rare but devastating events. Progressive collapse is one of the most devastating types of building failures, most often leading to costly damages, multiple injuries, and possible loss of life. Factors such as construction errors, miscommunication, poor inspections, or design flaws contribute to these progressive collapses, which have lead to many changes in building codes throughout the world. The U.S. General Services Administration (GSA) document and Unified Facility Criteria – Department of Defense (UFC – DoD), USA guideline provides the general guidelines to assess the potential for progressive collapse in RCC and Steel buildings. In present study G+5, G+10 and G+ 20 storied structures are analyzed using Linear and Non Linear Static Analysis procedures by both, GSA (2003) and UFC (2013) guidelines. The comparison is made between both available guidelines. To understand effect of geometrical irregularity, L-shaped buildings and Rectangular buildings are considered in present study. As the method of GSA guidelines have some drawbacks, researchers had developed a different method called Push – Down Analysis for progressive collapse which is also studied and compared with that of GSA method.*

Keywords: Tsunamis, GSA, Linear Analysis, Push down Analysis

1. INTRODUCTION

There have been countless instances of buildings gradually collapsing during construction. Low material strength, construction overload, and inappropriate construction practises have all been linked to these construction disasters [5]. Ones under construction have a higher chance of collapsing than the same buildings after completion, according to historical statistics. Buildings that are resistant to progressive collapse are not a new problem in structural engineering. Since the partial collapse of the Ronan Point apartment building in 1968, many structural engineers and academic scholars have been working to prevent further collapse.

2. GLIMPSE IN THE PAST

The partial collapse of the Ronan Point Apartment building in London, England in 1968 generated a widespread concern for progressive collapse of buildings in chain reaction mode, triggered by a local failure. The Ronan Point collapse was brought about by a gas explosion in an apartment on the 18th floor of a 22-story precast concrete building. The gas explosion blew out the exterior bearing wall of the apartment that caused the upper floor slab to fall.

Figure 1. Ronan Point Collapse

The falling debris of upper floor triggered the collapse of the floor below. As a result, the collapse of one corner of the building almost to the ground takes place as shown in Figure 1.1. Since the Ronan Point collapse was considered as ―progressive collapse" both in the vertical and horizontal directions that led to a total or a disproportionately large failure relative to an initiating local failure L'Ambiance Plaza was another large collapse that followed a progressive collapse failure pattern. It was a 16-story residential complex in Bridgeport, Connecticut, that was under construction. Two wings of post-tensioned concrete flat slabs supported on steel columns made up the structure. The lift-slab method of erection was used, which entailed casting all floor slabs at grade level, one on top of the other. Columns were inserted through holes left in the stack of slabs for this reason, in sections that were many storeys high. The slabs were jacked up the columns in groups after jacks were erected at the tops of the columns. At their permanent placements on the columns, the lower slabs were attached in sequence.
The lift slab technique was used to construct the construction, which required the floor sla bs to be cast on the ground and then raised into place by a jacking operation.The building collapsed completely on April 23, 1987, just after one of the jacking operations was comp leted (Figure 1.2).

Figure 2. Alferd Murrah Building Collapse

In another scenario, the Alfred P. Murrah Building in Oklahoma City, Oklahoma, was a federal government office building. Between 1970 and 1976, the Murrah Building was designed and built. The Murrah Building had a 9story reinforced concrete ordinary moment frame as its structural arrangement. The Murrah Building was t he target of a terrorist attack on the morning of April 19, 1995, when a truck bomb explod ed in front of its north side. The building suffered substantial structural damage as a result of the explosion. The Murrah Building's north side, which was immediately hit by the blast, suffered major structural damage. The north half of the rectangular footprint was destroyed in its entirety. The damage spanned the full length of the structure. The blast immediately destroyed three columns that supported the transfer girder on the third floor, causing the top stories to fall. It was believed that around half of the building's usable space had collapsed (Figure 1.2).

Terrorist activity caused the collapse of the US Marine Barracks in Lebanon (Figure 1.3). The structure was hit by two truck bombs, which caused the American embassy to gradually collapse. The blast destroyed the horseshoe-shaped building's whole central front, leaving balconies and offices in stacked levels of rubble and flinging masonry, metal, and glass pieces across a wide expanse. Aside from these, there are a number of other important events that contribute to the progressive collapse of structures, including:

- Kansas City Hyatt Regency Hotel Walk Way Collapse
- Skyline Plaza – premature formwork removal
- Civic Arena Roof collapse
- World Trade Centre
- Khobar Towers
- Jackson Landing Skating Ring – Excessive ice load

Figure 3. U. S. Marine Barracks Collapse

3. ANALYSIS PROCEDURE FOR PROGRESSIVE COLLAPSE

In order to analyze the structures and investigate their response to the progressive collapse phenomenon, there are several analytical methods. These methods vary extensively in respect to time consumption and the structural knowledge required to perform the analysis.

The most common analysis methods have been used to explore the general structural behaviour in order of increasing complexity are Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), Nonlinear Static Procedure (NSP), and Nonlinear Dynamic Procedure (NDP).

3.1. Linear static procedure

The linear static method is a basic approach and the simplest method for structural analysis. In this method the structural analysis incorporates only linear elastic materials and it is not considering the geometric and materials nonlinearity. Moreover, it is difficult to correctly predict the structural behaviour of the buildings particularly under blast or progressive collapse scenarios. For this reason, the implementation of this analysis method has some errors when compare with more sophisticated approaches. In

spite of these disadvantages, the linear static procedure is a popular method for analysis and design of the structures since it is quick, simple, and economic analysis approach.
In order to employ this method for progressive collapse simulation, critical columns are notionally removed from the structure and the gravity load is applied. The analysis was completed quickly and gives fundamental results to aid the analytic to conceptually grasp the behaviour of the structure. Subsequently, the response of the structure to the column removal is accessed via demand to capacity ratios (DCRs) for each element. Finally, some recommendations have been proposed by GSA guidelines for utilizing the linear static procedure for the evaluating progressive collapse potential. For instance, it should be used for regular (typical) structures, for routine analysis of low and medium rise building (not exceeding ten floors), and to account the dynamic influence by applying an amplified factor of "2" to the load combination.

3.2. Linear Dynamic Procedure

In general, the linear dynamic analysis method is more precise approach than linear static procedure. The accounting of the damping forces and inertia besides the considerable increase in the accuracy level of the analysis outcomes is the major advantages of this analysis approach. In addition to these benefits there is no necessity to estimate the dynamic amplification effects since they are being considered. Instead, this method has several drawbacks such as more complicity, time consumption, and not including the materials and geometric nonlinearity which is the main feature of the progressive collapse phenomenon. Furthermore, only those buildings expected to remain elastic during the progressive collapse event could be analyzed by this analysis approach. Lastly, in the implementation of the linear dynamic procedure the researcher has to be more aware for the buildings that have large plastic deformations due to the inaccurately computed dynamic parameters.

3.3. Nonlinear Static Procedure

Nonlinear static approach is a more intricate and accurate analysis method than the linear static procedure to identifying the progressive collapse in structures. This analysis method is known as pushover analysis and it is extensively used for the earthquake analysis (lateral load). The nonlinear static procedure is only one step above the linear static one since it allows capturing of both geometric and materials nonlinearity in which the most widespread model is an elastic-perfectly plastic curve. Although the materials and the geometric nonlinear behaviour are accounted for, but the dynamic effects still be neglected and the analytic should imply the amplification actor of "2" in the load's combination. Thus, this procedure provides limited improvement towards understanding the structural response. In the case of progressive collapse analysis, the structural behaviour is evaluated by applying a stepwise increase of vertical loads (incremental or iterative approach) until structure collapse or maximum loads are attained. These step by-step increases are complicated to be performed and time consuming. Additionally, the nonlinear static procedure generally leads to overly conservative findings during the structural analysis to assess the progressive collapse potential.

3.4. Nonlinear Dynamic Procedure

Nonlinear dynamic method is the most sophisticated and detailed structural analysis method. It performs if the structures are expected to experience nonlinear behaviour. This method is known in the structural engineering community as Time History analysis where the structural response is determined as a function of time. In time history analysis procedure inertial effects, nonlinearities for both geometry and materials including second order effects such as P-delta, and the dynamic nature are accounted. In this approach, an assumption has to be considered for the plastic hinges locations and their behaviour since the members are permitted to enter the inelastic range of deformation. Furthermore, the moment-rotation relationship is used to define the behaviour of the plastic hinges. The nonlinear dynamic approach (NLD) is the most integrated and vital method for progressive collapse potential assessment provides the most realistic and accurate results. In this evaluation, a critical load-carrying element is instantaneously removed, then the loads are applied without the amplification factor and structural materials are allowed to undergo nonlinear behaviour. Following this procedure, the loaded structure is analyzed. It should be mentioned that time history analysis is generally avoided because of its complexity and the enormous time to generate the model and the long amount of time to execute the model. Also, the evaluation and validation of the outcomes can become an economical concern.

4. ANALYTICAL MODELLING PROCEDURE

Computational progressive collapse analysis of the four case study apartments was conducted using the commercially available software, SAP2000 (V15). Linear static and non-linear static three-dimensional (3-D) computer models of each tested building using SAP2000. Different notional removal scenarios were carried out according to the guidelines mentioned. The models were analyzed and the outcomes were summarized.

5. COLUMN REMOVAL CASES

The sudden removals of the columns from the G+10 regular and irregular buildings are analyzed according to GSA guidelines and also the building vulnerability against progressive collapse (PC) is assessed. Using SAP 2000, removal of columns and their consequences have been modeled through the following case studies:

- Case 1: removal of column in the middle of long side of the building.
- Case2: removal of column in the middle of the short side of the building.
- Case3: the removal of column in the corner of the building.
- Case4: removal of column in the middle of the building.

Referring to each case, the locations of the removed columns in regular and irregular structure are shown in Figure 4.

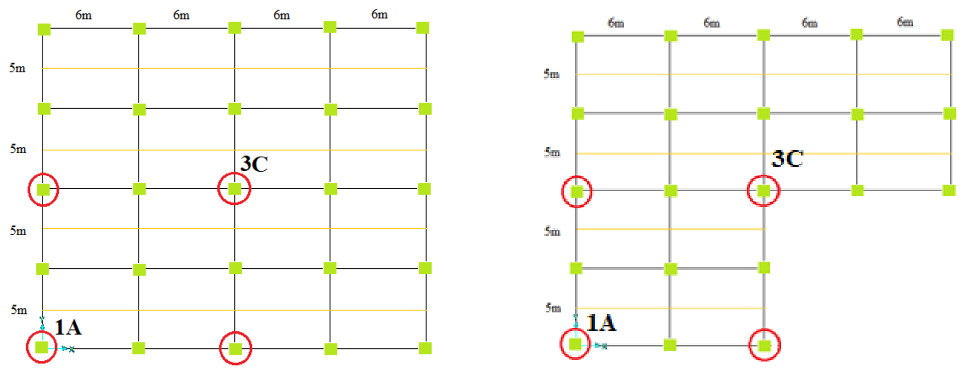

Figure 4. Column removal cases of regular and irregular structures

5.1. Middle column removal regular structure

Column 3C was selected as middle column removal case. The bending moment diagram and demand capacity ratio (DCR) calculated is shown in Figure 5. and 6.

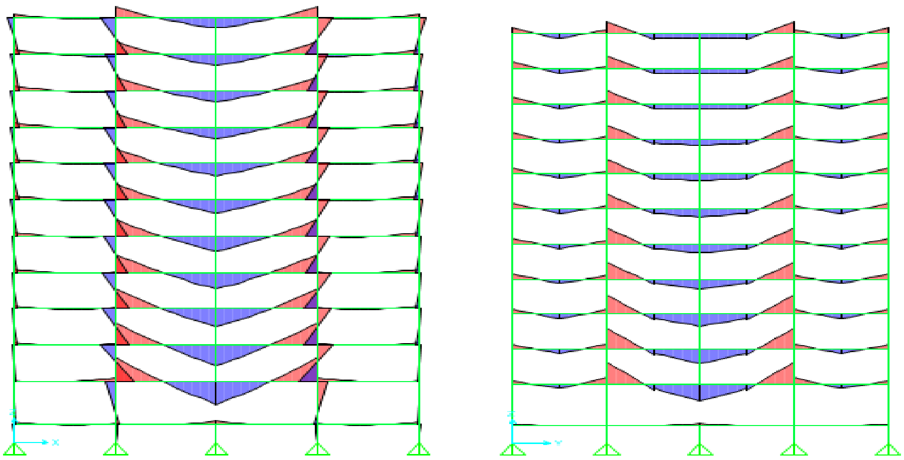

Figure 5. Bending moment diagram of the middle column removal

Figure 6. DCR value of the middle column removal

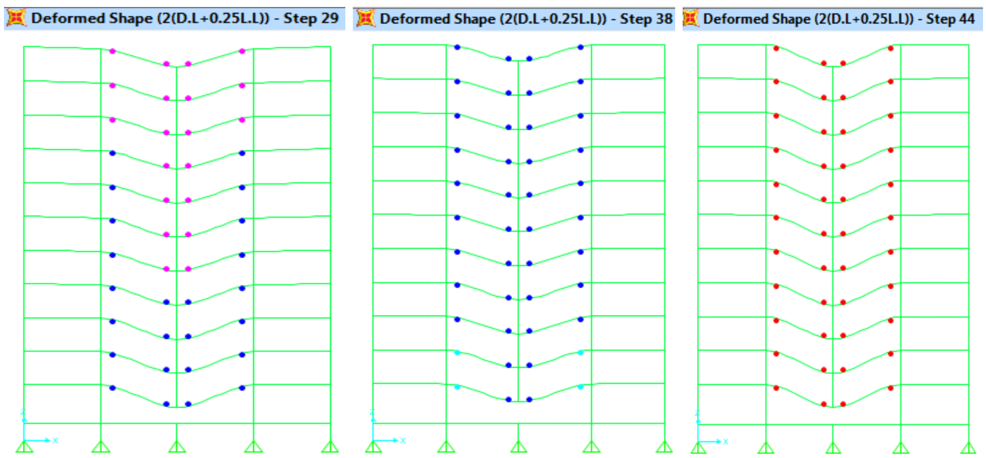

Figure 7. Plastic hinge formations in horizontal direction of the middle column removal

5.2. Corner column removal of regular structure

Column 1A was selected as corner column removal case. The bending moment diagram and demand capacity ratio (DCR) calculated is shown in Figure 7. and 8.

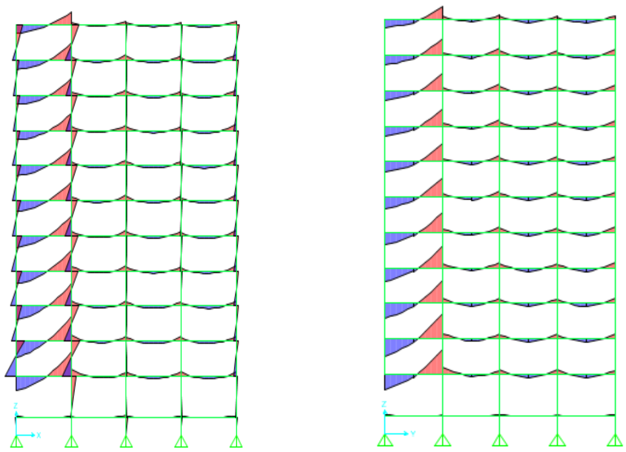

Figure 8. Bending moment diagram of the corner column removal

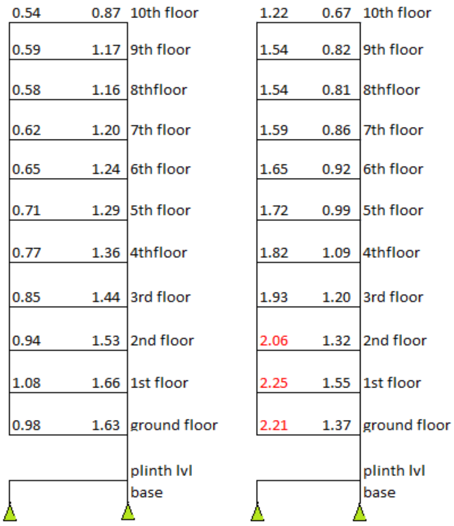

Figure 9. DCR value of the corner column removal

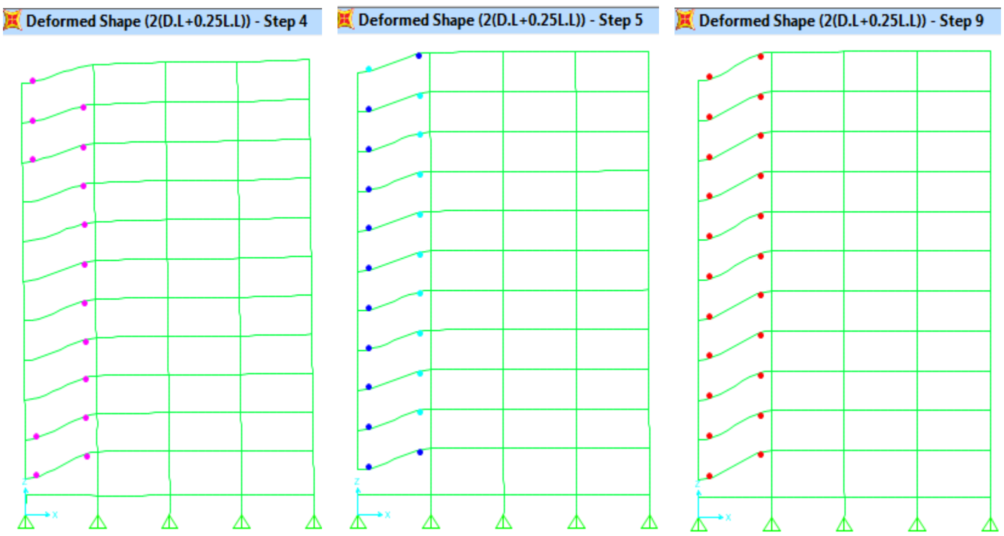

Figure 10. Plastic hinge formations in horizontal direction of the corner column removal

5.3. Percentage GSA load attempt

Percentage of load is found by summation of the reactions obtained at the supports for each analysis step divided by total load applied. In Nonlinear analysis structure is considered to have enough resistance against progressive collapse if the percentage load carried by the structure after loss of column exceeds 50%.

➢ Regular structure

Table 1: Percentage GSA load attempt in Non-Linear Static Analysis of regular structure

Nonlinear static case	GSA Loading	%GSA Load attempt
Longer	2(D. L+0. 25L.L)	56.22%
Shorter	2(D. L+0. 25L.L)	97.02%
Middle	2(D. L+0. 25L.L)	81.27%
Corner	2(D. L+0. 25L.L)	72.74%

➢ Irregular structure

Table 2: Percentage GSA load attempt in Non-Linear Static Analysis of irregular structure

Nonlinear static case	GSA Loading	%GSA Load attempt
Longer	2(D. L+0. 25L.L)	57.02%
Shorter	2(D. L+0. 25L.L)	86.08%
Middle	2(D. L+0. 25L.L)	65.92%
Corner	2(D. L+0. 25L.L)	73.68%

6. CONCLUSIONS

In this study linear static and non-linear static analysis procedures are carried out for progressive collapse analysis of G+10-storey moment resistant regular and irregular RC building. DCR are found out for beams and they are highly stressed nearby columns at all storeys for four column removal cases. It is observed that DCR in flexure in beam exceeds permissible limit of 2 in all column removal cases for regular structure and 1.5 in all column removal cases for irregular structure but the severity varies from each column removal cases. DCR calculated in flexure for beams by linear static analysis is higher on left and right side of column removal points.

Nonlinear static analysis is carried out to understand the hinge formations at yield and at collapse. Nonlinear static analysis gives maximum collapse load for all the column removal cases. In Nonlinear analysis structure is considered to have enough resistance against progressive collapse if the percentage load carried by the structure after loss of column exceeds 50%. Here both regular and irregular structures are resistant against progressive collapse for all column removal cases. From the study it can be concluded that among all the four column removal cases, corner column removal case are most affected for collapse.

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