Behaviour of 3D-Moment Resistant Steel Structure Further to Column Loss

Abhishek Ghimire

District Support Engineer, Nepal Reconstruction Authority, Nepal
abhi.ghimire45[at]gmail.com

Abstract: ***The present paper gives behaviour of 3D moment resistant steel structure further to column loss. Liege University performed and developed behaviour of structure in the field of robustness of building structures for the specific scenario ''loss of a column''. In particular, the static non- linear response of a steel building structure following a column loss will be first presented and then, parametrical studies of structure by varying the position of column loss will be described.***

Keywords: Robustness, Catenary Action, Member Forces, Column loss, nonlinear response.

1. Introduction

Recent events such as natural catastrophes or terrorism attacks have highlighted the necessity to ensure the structural integrity of buildings under an exceptional event. According to Eurocodes and some other national design codes, the structural integrity of civil engineering structures should be ensured through appropriate measures but, in most cases, no precise practical guidelines on how to achieve this goal are provided. At Liège University, the exceptional event "loss of a column" in a building structure is under investigation, using experimental, numerical and analytical approaches with the final objective to propose design requirements to ensure an appropriate robustness under the considered scenario.

The present paper reflects the recent investigation behaviour of 3D Moment resistant steel structure further to column loss and will mainly focus on the static behaviour of the structure. Firstly, the general philosophy and adopted strategy aiming at deriving design requirements will be presented and then achievements obtained through parametrical study of structure will be given.

2. General philosophy and adopted strategy

The present section describes the global strategy adopted at Liege University. The presented study is dedicated to frame only composed of columns and beams; the possible beneficial effect of the slab is presently neglected in the developments. When a frame is submitted to a column loss, two parts can be identified in the structure: the directly affected part and the indirectly affected part. The directly affected part contains all the beams, columns and beam-to-column joints located just above the lost column (Figure 1). The rest of the structure (i.e. the lateral parts and the storeys under the lost column) is defined as the indirectly affected part.

When the frame loses one of its columns (column AB in Figure 1a), the evolution of the compression force N_{AB} in this element VS the vertical displacement (u) at the top of this column is divided in 3 phases as illustrated in Figure 1. During phase 1 (from (1) to (2) in Figure 1b), i.e. before the event, the column is "normally" loaded (i.e. the column supports the loads coming from the upper storeys) and the corresponding load is named $N_{ABnormal}$.

Phase 2 (from (2) to (4) in Figure 1b) begins when the event occurs and the column progressively loses its axial resistance. During this phase, a plastic mechanism develops in the directly affected part. Each change of slope in the curve of Figure 1b corresponds to the development of a new hinge in the directly affected part, until reaching a complete plastic mechanism (point (4) in Figure 1b). Phase 3 (from (4) to (5) in Figure 1b) starts when this plastic mechanism is formed: the vertical displacement at the top of the lost column increases significantly since there is no more first order rigidity in the structure. As a result of these large displacements, catenary actions develop progressively in the beams of the directly affected part, so providing a second-order stiffness to the structure. The role of the indirectly affected part during phase 3 is to provide a lateral anchorage to these catenary actions: the stiffer the indirectly affected part is, the higher the catenary actions will be in the directly affected part. In the extreme situation where the indirectly affected part has no lateral stiffness, then no catenary actions will develop and phase 3 will not develop.

The behaviour of the actual structure from (2) to (5) (Figure 1b) may be predicted simulating the behaviour of the structure as shown in Figure 2; the frame without the lost column AB is subjected to a concentrated load P going downward and applied at node A.

The objective with the analytical method developed in Liege is to determine a P-u curve reflecting the behaviour of the simulated structure, to estimate the redistribution of loads within the structure during these phases and finally to check whether the structure is able or not to reach point (5), i.e. when P $=N_{ABnormal}$. Indeed, this point is reached only if there is enough resistance and ductility in the damaged structure to sustain these large displacements and associated forces coming from the activation of alternative load paths.

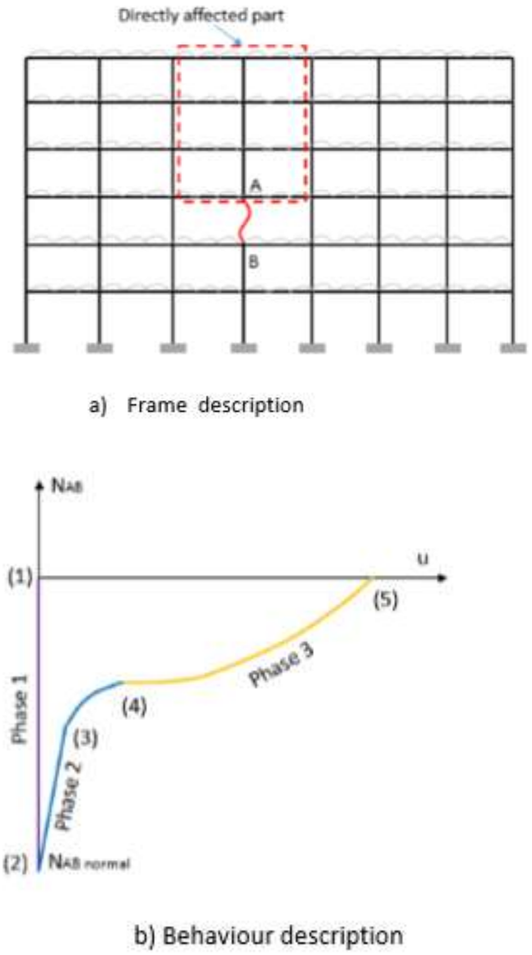

Figure 1: Behaviour of a frame submitted to a column loss

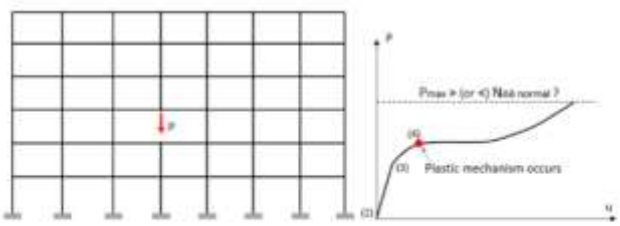

Figure 2: Simulation of the column loss

3. Steel Building Structure under loss of column

3.1 Introduction

The main objective of this study is to investigate practical guideline for robustness design of typical multi-story building. The reference building used for the study is office building and location of the site is in Brussels area of Belgium. Building structure consist of 4 spans in X-direction with span length 6m, 3 spans in Y-direction with span length 6m and four stories of 3.5m height on each which is shown in figure 3.

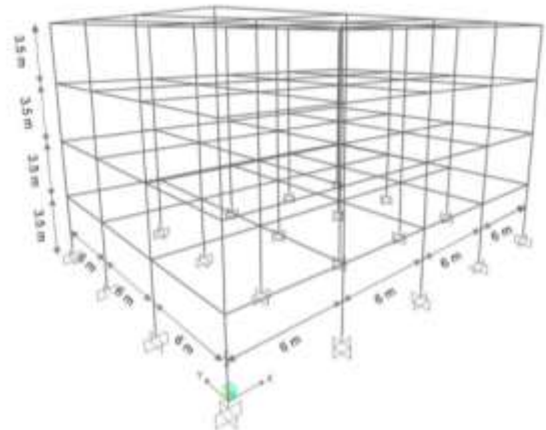

Figure 3: Reference 3D-Steel Structure of office building

Considered reference structure of building consists of full moment resistant and ductile joints with restrained supports and having sufficient rotation capacity. However, it is necessary to make sure that structure should has adequate ductility to reach the maximum deflection which is crucial to develop catenary action without any failure. Structure has been designed according to Eurocode (EN1990) provision for Ultimate and serviceability limit states checks.

3.2 Behaviour of structure under loss of column

In this section of paper, the behaviour of the structure further to loss of column is investigated. The contribution of the secondary frame and 3D effects are also considered. This investigation is based on a geometrical and material non-linear analysis. The design approach described in a topic of General philosophy and adopted strategy, is followed to study the redistribution of forces in the structure during the static loss of column.

The alternative load path method is used according to EN1991-1-7 taking into account the elasto-plastic behaviour and the second order effects. The tool used in analyzing structural behaviour under exceptional loads is CEPAO, a homemade software developed in Liege University to perform plastic hinges analysis taking into consideration second order and buckling analysis, further information about this software can be found in PhD thesis of Hoang L.V. During numerical analysis of the structure, if the structure remains globally stable until load factor $\lambda = 1$, which corresponds to the complete loss of column, the structure is considered as robust.

The graph of figure 6, shows the evolution of the vertical displacement at the top of the loss column A (figure 4) versus the load factor (λ) in accidental limit state load combination. It can be noticed that the structure is stable after the complete loss of column. As, it mentioned above that if the structure remains globally stable until $\lambda = 1$, which corresponds to the complete loss of column, the structure is considered as robust. So, structure can be considered as robust structure under loss of column scenario.

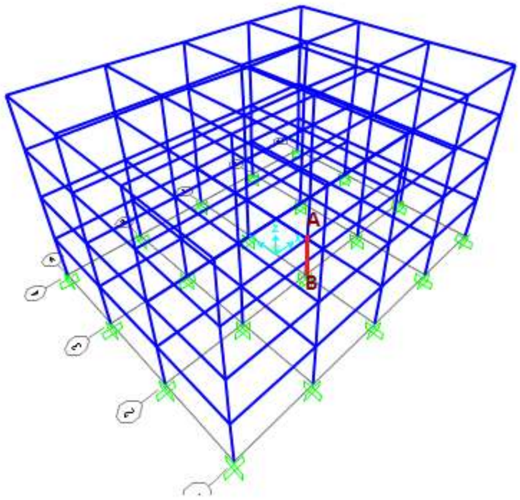

Figure 4: Structure before column loss

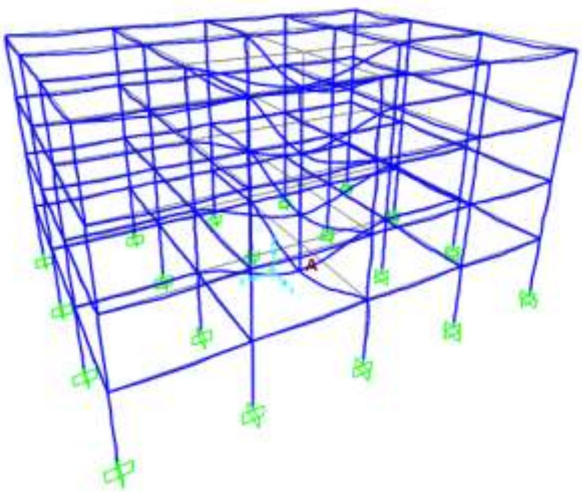

Figure 5: Structure after column loss

The behaviour of the structure during column loss can be decomposed in the following phases, which can easily be observed in figure 6. During the first phase, structure behaves elastically. When the moment at the beam end reaches the value of the resistant moment of the joint, which is smaller than the plastic moment of the beam, a plastic hinge forms in the joint.

The point at which load factor $\lambda = 0.80$, is the ending of elastic stage of phase 2. This is the point up to which structure shows fully elastic behaviour. This is the formation point of first plastic hinge in the structure. After that plastic hinges appear quasi simultaneously at all floors and for every change of the slope in the curve represent the formation of plastic hinges. The formation of global beam plastic mechanism in the directly affected part of the structure happened when $\lambda = 1.44$, which is the start point of phase 3. This mechanism is completed when plastic hinges appear at mid-length of the double-beams at each floor of the directly affected part.

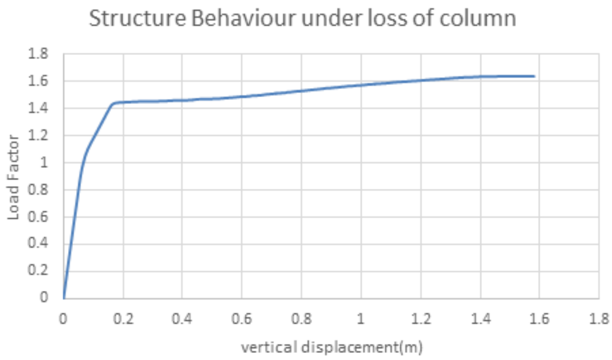

Figure 6: Vertical displacement at the top of falling column versus load factor

When plastic mechanism has formed in the directly affected part, the vertical displacement at the top of the loss column rapidly increase due to loss of bending stiffness in the joint of the directly affected part of both primary and secondary frames. Tension forces are developed in the bottom beam just above the lost column. The axial stiffness of the beam is activated due to these membrane effects and the deformation rate progressively decreases until yielding starts to develop in the indirectly affected part. The failure mode corresponds to the formation of plastic mechanism in the indirectly affected parts for $\lambda = 1.64$ (Figure 7); but the load can still increase a little. Finally, the frame becomes unstable after column has been completely removed.

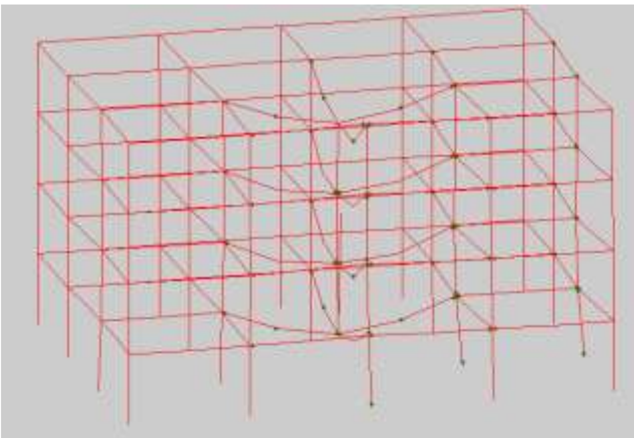

Figure 7: Plastic Mechanism in the indirectly affected parts

Two main behaviour types are highlighted during the static loss of column. The first one is called flexural behaviour and is related with bending of directly affected part beams. This is only behaviour types which are activated during phases 1 and 2, i.e. before the global plastic mechanism has appeared in the directly affected part. The load factor at beams plastic mechanism threshold is 1.44 (see on figure 6). Which means that the structure is able to resist exceptional events before reaching the beam plastic mechanism.

The second behaviour type (member behaviour) is related to the development of significant tension forces (catenary action) in the directly affected beams after reaching the beam plastic mechanism until reach a full plastic mechanism in the frame. These membrane effects constitute an additional contribution to sustain the column loss.

3.3 Comparison between 2D and 3D behaviour under loss of column

The graph of figure 8, shows the evolution of the vertical displacement at the top of the loss column versus the load factor (λ) in reference 3D steel structure which includes both the numerical results of primary and secondary frame.

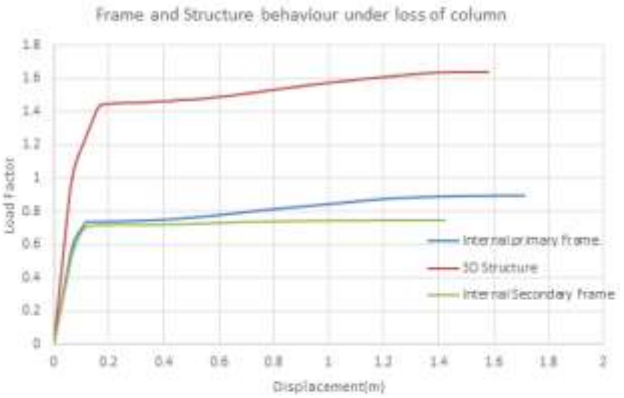

Figure 8: Comparison between frame and structure behaviour

It can be noticed that the internal primary and secondary frames become unstable before the complete loss of column i.e. when column has loss 89.48% and 74.67% of the force respectively which they were initially sustaining. But when analysising result from the 3D structure, it is stable after the complete loss of column.

One of the important flexural behaviour of the structure, which is related with bending of directly affected part influenced by the combine effect of primary and secondary frames. Separately, primary and secondary frame's beam plastic mechanism occurred at $\lambda = 0.737$ & 0.727 respectively, while due to increase the area of directly affected part it is occurred at to $\lambda = 1.44$ for the 3D structure. And it is clearly understandable that structure is robust and enough to sustain exceptional events before complete beam plastic mechanism.

The second behaviour, member behaviour which is related with the development of tension forces in the beams just above the lost column also influenced by the contribution of both primary and secondary frames. Due to the effect of 3D structure, number of beams above the lost column increased and consequently the transferred paths of these loads to the indirectly affected part is more than that of single frame.

Due to increase area of directly as well as indirectly affected part for beam plastic mechanism and to transfer the tension load which raised due to loss of column, 3D structure can sustain the exceptional load further to column loss better than that of the single frame.

3.4 Robustness assessment of the structure by varying position of column loss

The graph figure 10, represented the structure behaviour under loss of column at different position (figure 9). For all cases, it can be noticed that the structure is robust to sustain load at the time of exceptional event of column loss. It is not much more significant to do parametrical study by increasing horizontal spans or vertical stories because at the end it shows same behaviour.

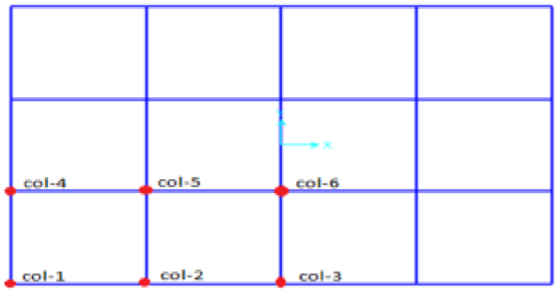

Figure 9: Position of column loss

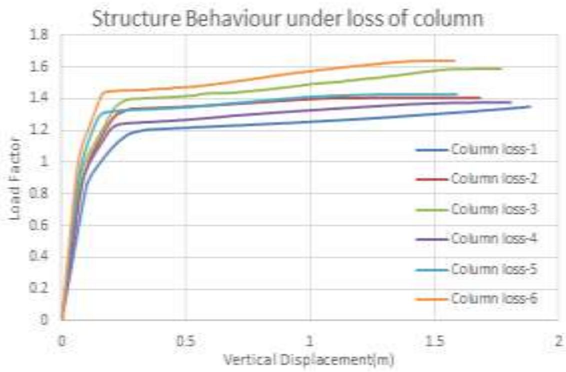

Figure 10: Structure behaviour after loss of column

4. Discussion and Conclusion

The main objectives of this paper is to identify the structural requirements for robustness design of steel structures further to exceptional event ''loss of column''. These requirements were studied through the investigation based on a geometrical and material non-linear analysis of 3D steel structures by evaluating the structural behaviour of normal multi-story moment resistant steel structure. Finally, it is concluded that reference structure is robust enough to sustain exceptional event 'column loss' if the contribution of secondary frame and 3D effects are considered. But, the frame itself is not robust; if there is not consideration of the contribution by secondary frame and 3D effects on it. At that time, it is necessary to upgrade frame to sustain exceptional event 'loss of column'. This conclusion could simplify life of engineer in question of robustness design.

Assumptions are one of the major factors which influences and limited the scope of the investigation. To achieve the objectives of present work, several assumptions have been set from the beginning of the task. Present paper only studied the behaviour of moment resistant structure of full moment resistant and ductile joints with restrained supports and having sufficient rotation capacity. Therefore, finding solutions only valid for these types of structures. In order to cover different types of structural configuration, some recommendations are preferred for further study.

1. Behaviour of moment resistant structure with partially strength, semi-rigid joint further to column loss is one of the important consideration and influence factor for the investigation of structural robustness.
2. Behaviour of structure further to loss of more than one column at the same time is one of the interesting topic for structural robustness.

References

[1] *EN 1991-1-7;2006,Eurocode 1-Actions on structures Part 1-7;General actions.* **Standardization, European Committee For.** Brussels : s.n., 2006.

[2] *Automatic plastic-hinge analysis and design of 3D steel frames, PhD thesis.* **Hoang, L. V.** Liège : Liège University, 2008.

[3] Steel and composite building frames: sway response under conventional loading and developmet of membrane effects in beams further to an exceptional action, PhD Thesis. **Demonceau, J.-F**. Liège University, Liège : s.n., 2008.

[4] EN 1991-1-1:2002, **Eurocode 1**: Actions on structures - Part 1-1: General actions -Densities, selfweight, imposed loads for buildings. Standardization, European Committee For. Brussels : s.n., 2002

[5] Eurocode - Basis of structural design. **EUROPEAN STANDARD**, EN 1990. 2002.

[6] EN 1991-1-3; Actions on structures-General actions-Snow loads. Standardization, European Committee for. 2003.

[7] EN 1991-1-4; Actions on structures-General actions-Wind actions. standardization, European Committee for. 2005

[8] EN 1993-1-1; Design of steel structure-General rules and rules for building. Standardization, European Committee for. 2005.

[9] Robustness of steel building structures following a column loss, research paper. **Clara Huvelle, Jean-Pierre Jaspart, Jean-François Demonceau**

[10] Robustness of 3D steel structure further to column loss: Identification of structural requirements through parametrical studies, Master thesis. **Abhishek Ghimire**, University of Liege, 2016.

Author Profile

Abhishek Ghimire received the Bachelor in Civil Engineering from Pokhara University, Nepal in 2011. Mater in Civil Engineering from Erasmus Mundus Master Program Sustainable Construction under Natural Hazard and Catastrophic Events (Lulea Technical University, Sweden; University of Naples, Federico II, Italy; Liege University Belgium) in 2016 specialization on Steel Structure. During 2012-2016, he worked as Civil Engineer and Senior Civil Engineer at Sagarmatha Engineering Consultancy, Pokhara, Energy and Environmental officer at Kaski Development Committee, Government of Nepal. After Master degree, he worked as a Full Time Lecturer at Lalitpur Engineering College, Institute of Engineering and part time Lecturer at Nepal Engineering College, Kantipur City College. Currently, he works in the field of reconstruction to make earthquake resistant building after massive earthquake 2015 at Sindhupal chowk district of Nepal as a District Support Engineer (DSE) which is facilitated by United Nation Development Program (UNDP) and Under Nepal Reconstruction Authority, Nepal.