HOW TO CHECK ANALYTICALLY THE ROBUSTNESS OF A BUILDING SUBMITTED TO A COLUMN LOSS – A PREMIERE

Clara Huvelle, Jean-Pierre Jaspart, Jean-François Demonceau

University of Liege, Argenco dptmt, Belgium
jean-pierre.jaspart@ulg.ac.be, jfdemonceau@ulg.ac.be

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 guaranteed through appropriate measures and one way to guarantee it is to ensure an appropriate robustness of the structure, which may be defined as the ability of a structure to remain globally stable in case of exceptional event leading to local damages. However, although global design approaches are provided in modern codes and standards, no easy-to-apply practical guidelines are provided. The present paper reflects recent researches realised at the University of Liege with the scope of proposing such practical guidelines for the activation of alternative load path in the structure, design strategy generally leading to the most economical solutions.

1 BACKGROUND

At the University of Liege, the exceptional event "loss of a column" in steel and composite plane frames is under investigation since several years, using experimental, numerical and analytical approaches. The general philosophy adopted at the University of Liege is to observe the redistribution of the loads in damaged structures through the activation of alternative load paths and to develop analytical methods to predict this redistribution of loads. Knowing how the loads redistribute, it is possible to estimate whether or not the remaining elements are able to sustain the additional loads coming from this redistribution, without causing a progressive collapse of the entire frame.

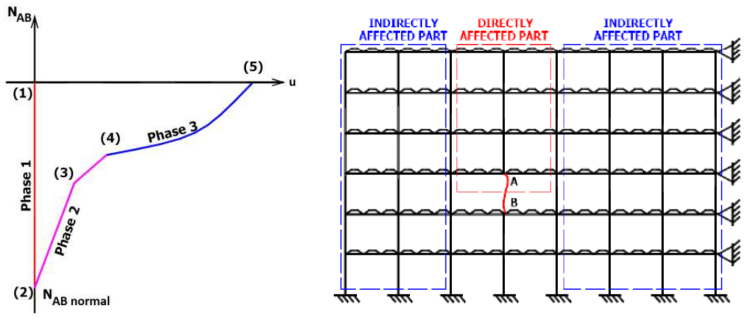


Fig. 1. N-u curve ([1] and [2])

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 one (*Fig. 1*). The directly affected part contains all the beams, columns and beam-to-column joints located just above the lost column. The rest of the structure (i.e the lateral parts and the storeys under the lost column) is defined as the indirectly affected part. For a frame that losses one of its columns (column AB in *Fig. 1*), 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 *Fig. 1*. During phase 1 (from (1) to (2)), the column is "normally" loaded (i.e. the column supports the loads coming from the upper storeys) and the load in the column before its disappearance is defined as equal to $N_{ABnormal}$. Phase 2 (from (2) to (4)) begins when the column starts to disappears. During phase 2, a plastic mechanism develops in the directly affected part. Each change of slope in the curve of *Fig. 1* corresponds to the development of a new hinge in the directly affected part, until reaching a complete plastic mechanism (point (4)). Phase 3 (from (4) to (5)) starts when this plastic mechanism is formed: the vertical displacement at the top of the column increases significantly since there is no more first-order stiffness in the structure. Due to these large displacements, catenary actions are developing in the beams of the directly affected part, giving 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 more catenary action will develop in the directly affected part.

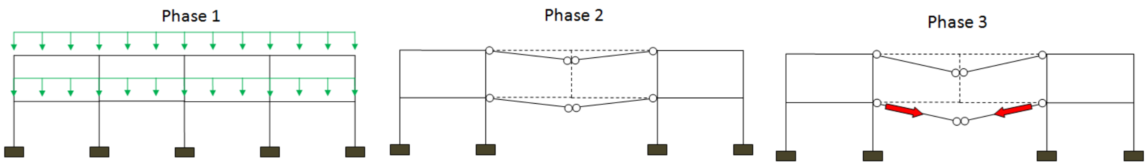


Fig. 2. Description of the phases

The objective with the analytical method developed in Liege is to determine a curve P-u reflecting the behaviour of the structure during phase 2 and 3, to be able to estimate the redistribution of loads within the structures during these phases and to be able to finally check if the structure is able to reach point (5) of *Fig. 1*. Indeed, this point is reached only if there is enough resistance and ductility in the damaged structure to sustain these large displacements and additional forces coming from the activation of alternative load paths. *Fig. 2* illustrates the 3 phases described here above.
In Demonceau's thesis [1], an analytical method has been developed that allows predicting the curve P-u during phase 3, for the case of a 2D structure losing statically one column. The method is focusing on phase 3, i.e. when second order effects are predominant, and is based on the study of a substructure that contains only the lower beams of the directly affected part (*Fig. 3*), identified as the beam where higher tension forces appear. The surrounding structure is simulated by a horizontal spring with a stiffness K_H (*Fig. 3*). This K_H has a constant value in the model, because the indirectly affected is assumed to remain elastic during phase 3.

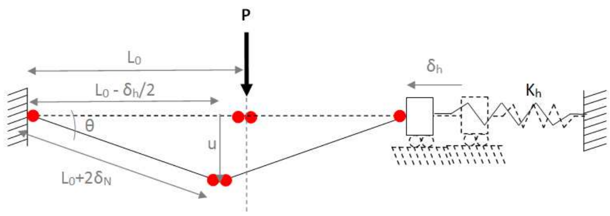


Fig. 3. Demonceau's substructure

The input data's of this method are the following:
– L_0 : initial length of the beam;
– M-N resistance interaction curve for both hogging and sagging bending in the plastic hinge;
– K_H: stiffness of the horizontal spring;
– K_N: axial stiffness of a plastic hinge submitted to both bending and axial forces (linking N to the plastic elongation of the hinge δ_N).

Within [1], K_N had to be numerically computed or extracted from experimental results; there was no analytical method to determine this parameter.
In the two next sections, it will be explained how this model has been improved through recent developments, in particular for the prediction of the K_N and K_H values. Then, the global analytical method able to predict the response of a 2D frame further to a column loss will be presented.

2 LOCAL PARAMETER K_N

The K_N parameter is defined as a local parameter, because it is linked to the behaviour of the yielded zones in the directly affected part. These yielded zones can occur in the beam cross section

or in the beam-to-column joint if partial strength joints are used. The present section will focus on the case where the hinge develops in the beam cross section. However, a method founded on the same philosophy is also available for the case where the hinges develop in the beam-to-column joints.
To define an analytical model for the prediction of K_N, it is required to define a length for the plastic hinge. This hinge length L is defined according to [3] (*Fig. 4*).

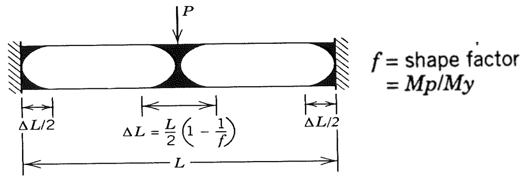


Fig. 4. Definition of the hinge length ([3])

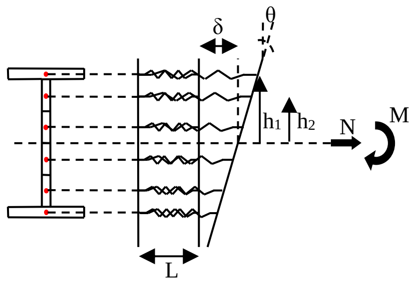


Fig. 5. Simulation of the plastic hinge

Then, the cross section is fictively divided into 6 parts: 2 parts represent the flanges and 4 parts the web (*Fig. 5*). Finally, the extremities of the beams of the directly affected part can be considered as 6 springs in parallel submitted to M and N, assuming that the section at the extremities of these springs remains straight, using the Bernoulli assumption (*Fig. 5*).

The force-displacement laws of each spring are elastic-perfectly plastic, without limitation of ductility and symmetric in tension and in compression. The resistance of each spring is simply equal to $F_{rdi} = A_i*f_y$ and the stiffness $K_i = E*A_i/L$, where A_i represents the section of part "i" and E the Young modulus of the beam material.
According to parametrical studies, the value of K_N was strongly dependant on the value of the horizontal restraint K_H. So, as there is a coupling between this local parameter K_N and the global structure in which the hinge is developing, through the parameter K_H, the local hinge model has to be implemented in the substructure of Demonceau (*Fig. 6*).

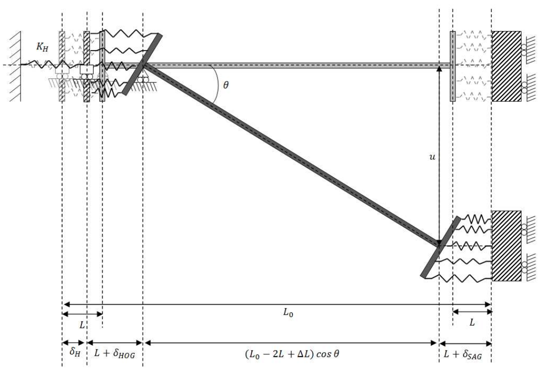


Fig. 6. New substructure model

There is no need anymore to define a M-N resistance curve or to explicitly determine K_N linking N to δ_N, because these data are implicitly included in the definition of the stiffness's and resistances of the springs simulating the hinges at the extremities of the beam.

3 GLOBAL PARAMETER K_H

As previously said, the substructure defined by Demonceau to study phase 3 was composed only with the lower beam of the directly affected part, i.e. the beams just above lost column. The rest of the structure (i.e. the indirectly affected part) was represented by one horizontal spring (see *Fig. 3*). However, this substructure is only valid if the compression force in the column just above the lost one remains constant during the all duration of phase 3, which is not always the case, as it has been demonstrated in [4] and [5]. This can be understood by comparing the behaviour of two structures as shown in *Fig. 7*. In the frame on the left, the indirectly affected part sags on the directly affected one, and the compression force in the column above the lost one can either increase or remain constant. In the frame on the right, no horizontal displacement is allowed, and the upper stories help the lower beam to support the loss of the column. In this case, the effort in the upper column may even go into tension.

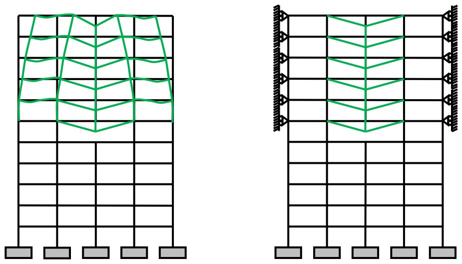


Fig. 7. Couplings between the stories of the directly affected part

These considerations have brought into light important coupling effects between the stories of the directly affected part, and also between the directly affected part and the indirectly affected part. Actually, it is just as if a vertical spring was missing in the substructure defined by Demonceau, i.e. a spring that could simulate the effect of the upper stories of the directly affected part.

A general approach has been developed for the determination of the parameter K_H to take into account these coupling effects. A first method is presented in [6] without taking into account the effects of K_N on these couplings. The next paragraph will describe precisely the complete analytical method taking into account the effects of both K_N and K_H.

4 COMPLETE ANALYTICAL MODEL

The substructure defined by Demonceau is generalized for all the stories of the directly affected part (*Fig. 8*) and the effects of K_N are added to this generalized substructure by considering the extremities of the beams with springs in parallel. On the other hand, the influence of the indirectly affected part is taken into account by considering horizontal springs at each extremities of the so-defined substructure.

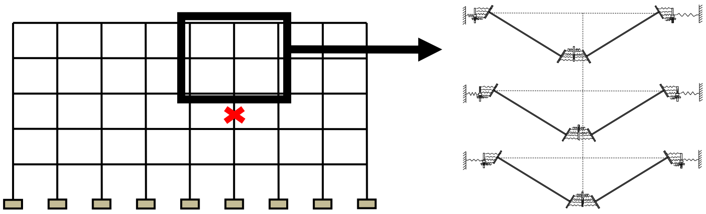


Fig. 8. New generalized substructure

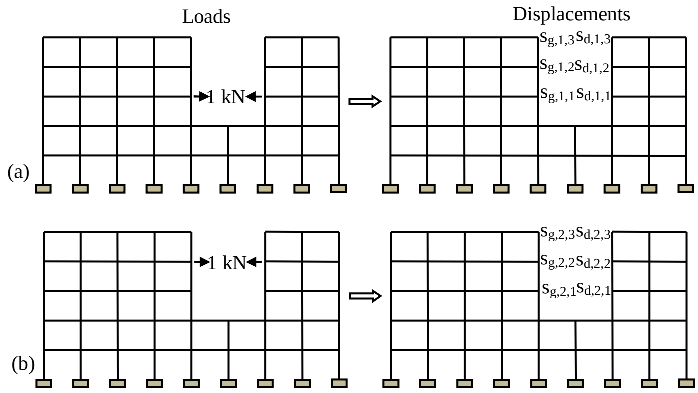


Fig. 9. Lateral stiffness matrix representing the indirectly affected part

These springs simulating the restraint of the indirectly affected part are defined by relations between the horizontal displacement δ_{Hi} at the storey i when a horizontal force F_{Hj} is acting at the level j: $\delta_{Hi} = \sum s_{ij} F_{Hj}$. The coefficients s_{ij} form the flexibility matrix of the indirectly affected part, s_{ij} being the horizontal displacement at the level i when a unitary horizontal force acts at the level j (*Fig. 9*). The flexibility matrix needs to be defined for both right and left parts of the substructure if the indirectly affected part is not symmetrical. The input data's for the final analytical model are the following:

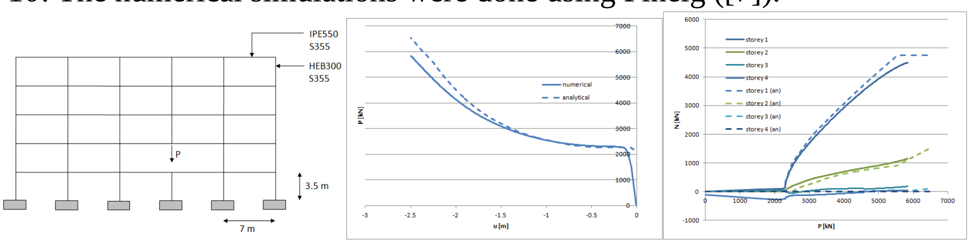
Table 1. Input data's of the analytical model

Cross section's characteristics of the beams and columns of the frame
Material information E, f_y
Frame dimensions: L_0: span of the beams H_0: height of the columns
Lost column localisation: n_{st} = number of stories of the directly affected part (= # of beams above the lost column) n = # of stories under the lost column c = # of columns in the indirectly affected part (left and right if not symmetrical)

Table 2. Unknowns and equations of the analytical model

Unknowns	Number	Equations	Number
u	1	u = input data's	1
θ	n_{st}	$\sin(\theta)=u/(L_0-2L+\Delta_L)$	n_{st}
δ	n_{st}	$\cos(\theta)=(L_0-2L-\delta_H-2\delta)/(L_0-2L+\Delta_L)$	n_{st}
$\delta_{H,g}$	n_{st}	$\delta_{H,g}(n_{st}x1)=S_g(n_{st}xn_{st})*F_H(n_{st}x1)$	n_{st}
$\delta_{H,d}$	n_{st}	$\delta_{H,d}(n_{st}x1)=S_d(n_{st}xn_{st})*F_H(n_{st}x1)$	n_{st}
Δ_L	n_{st}	$\Delta_L=F_H(L_0-2L)/(EA)$	n_{st}
M	n_{st}	$M=\sum F_i*h_i$	n_{st}
F_H	n_{st}	$F_H=\sum F_i$	n_{st}
F_i (i=[1:6])	6* n_{st}	$Fi=f(\delta_i)$	6* n_{st}
δ_i (i=[1:6])	6* n_{st}	$\delta_i=\delta+h_i*\theta$	6* n_{st}
P	n_{st}	$-0.5*P*(L_0-0.5*(\delta_{H,g}+\delta_{H,d}))+F_H*u+2*M=0$	n_{st}
P_{tot}	1	$P_{tot}=\sum P$	1

The validation of the proposed model has been validated through several comparison between numerical and analytical results obtained for the frame described in *Fig. 10*, in which the beam-to-column joints are assumed to be full-strength and fully rigid. One example of such comparisons is given in *Fig. 10*. The numerical simulations were done using Finelg ([7]).



(a) (b)

Fig. 10. Validation the complete analytical model through comparison to numerical results

Note that the model is applicable also when the plastic hinge develops in a partially resisting joint. In this case, the simulation of the plastic hinge is still a set of horizontal springs in parallel, one spring by component row, and the characteristics of these elastoplastic springs (stiffness and resistance) are determined using the component method, as recommended in the Eurocode ([8]). The springs are non symmetrical and are only active in tension or in compression. This model for the partially resisting joint has been validated through an experimental test conducted at Liege University in 2008, for a composite beams submitted to the loss of it central support (*Fig. 11*). For more details, refer to [9][10][11]

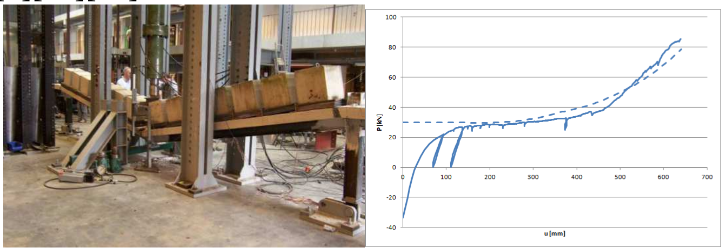


Fig. 11. Experimental test conducted in Liege (P-u curve)

5 DISCUSSION AND CONCLUSION

The fully analytical method presented in this paper allows predicting the response of a frame submitted to a column loss, what is a premiere. The developed method takes into account of the following phenomena:

- the global interaction between the different parts of the structure;
- the local phenomena happening in the yielded zones, submitted to both M and N.

The method presented here deals with 2D frames, submitted to a static column loss. Also, it is assumed that the indirectly affected part remains elastic and so, the horizontal restrain brought by the indirectly affected part is constant during phase 3.

Other research works have also been conducted in Liege to deal with aspects such as the 3D behaviour of structures, the possible dynamic effects associated to a column loss and the yielding of the indirectly affected part ([4], [12] and [5] respectively).

The final aim of these developments is to be able to propose soon guidelines, design recommendations or easy-to-use software, founded on a good knowledge of the structural behaviour to help the practitioners in design offices with the robustness issues they can meet in practice.

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