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Complete analytical procedure to assess the response of a frame submitted to a column loss

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ABSTRACT

The present paper gives a global overview on recent developments performed at the University of Liege on structural robustness of buildings for the specific scenario “loss of a column”. In particular, a complete analytical method to assess the response of a 2D frame losing statically one of its columns is presented in details. This method is based on the development of alternative load paths in the damaged structure and takes into account the couplings between the different parts of the structure which are differently affected by the column loss. Also, the validation of the developed method through comparison to experimental and numerical evidences is presented.

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 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 such as the activation of alternative load paths or the key element method 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 objective of proposing such practical guidelines for the activation of alternative load paths in the structure, knowing that this design strategy generally leads to the most economical solutions.

2. Background

The behaviour of steel and composite frames under the exceptional event “loss of a column” have been recently investigated through many researches (e.g. from [1–13] among others).

At the University of Liege, this topic is under investigation since many years using experimental, numerical and analytical approaches [2]. The adopted general philosophy in 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 are redistributed, 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.

Two PhD theses have already been finalised on these topics in Liege [4,11]. These theses have contributed to the development of a first analytical method that allows predicting the response of frames submitted to a column loss, and in particular, the associated catenary actions. This initial method has been recently improved and completed. The present paper gives a precise description of this improved analytical procedure.

2.1. General philosophy

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 (Fig. 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.

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Nomenclature

N_{AB}	compression force in the column
$N_{AB,normal}$	compression force in the column before it disappears
P	force simulating the loss of the column
u	vertical displacement at the top of the lost column
K_H	stiffness of the horizontal spring simulating the lateral restraint of the indirectly affected part
F_H	horizontal force acting on the spring K_H
δ_H	horizontal elongation of the spring K_H
K_N	axial stiffness of a plastic hinge submitted to bending and axial force
δ_N	axial elongation a plastic hinge submitted to bending and axial force
N	axial force in the beams of the directly affected part
M	bending moment at the extremities of the beams of the directly affected part
θ	rotation at the extremities of the beams of the directly affected part
L_0	initial length of the beams
ΔL	elastic elongation of the beams of the directly affected part
L	length of the plastic hinge (plasticized zones)
s_{ij}	displacement at the storey i for a force acting at the level j of the indirectly affected part
n_{st}	number of the storey of the directly affected part (above the lost column)

When the frame loses one of its columns (column AB in Fig. 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 Fig. 1. During phase 1 (from (1) to (2) in Fig. 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 $N_{AB,normal}$.

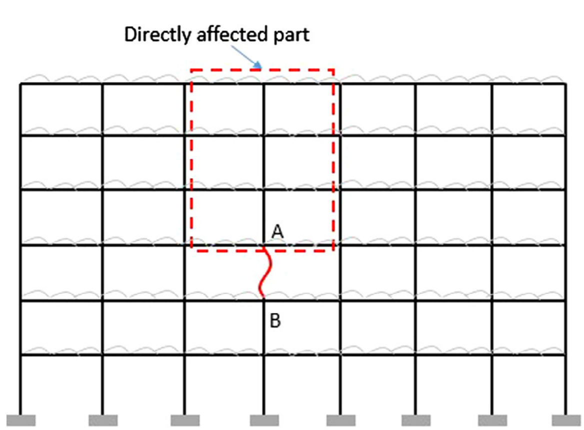
Phase 2 (from (2) to (4) in Fig. 1b) begins when the event occurs and the column progressively loses its axial resistance. During this phase, a plastic mechanism develops in the directly affected part. Each change of slope in the curve of Fig. 1b corresponds to the development of a new hinge in the directly affected part, until reaching a complete plastic mechanism (point (4) in Fig. 1b). Phase 3 (from (4) to (5) in Fig. 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.

Table 1
Unknowns and equations of the Demonceau model.

Unknowns	Equations
u	u = input data
θ	$\sin(\theta) = u/(L_0 + 2\delta_N)$
δ_h	$\cos(\theta) = (L_0 - \delta_H/2)/(L_0 + 2\delta_N)$
δ_N	$\delta_H = F_H/K_H$
P	$\delta_N = N/K_N$
N	$M = f(N)$ ([1] or [17])
M	$-0.25P(L_0 - 0.5\delta_H) + 0.5F_H u + 2M = 0$
F_h	$N = F_H\cos(\theta) + 0.5P\sin(\theta)$

The behaviour of the actual structure from (2) to (5) (Fig. 1b) may be predicted simulating the behaviour of the structure as shown in Fig. 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 $P = N_{AB,normal}$. 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.



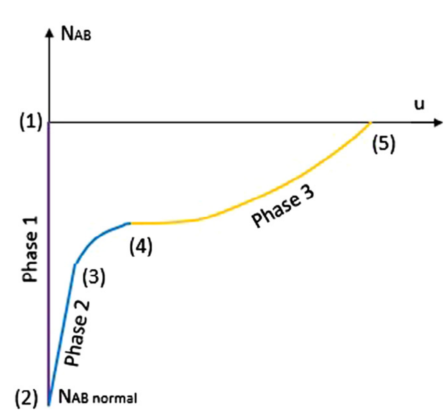


Fig. 1. Behaviour of a frame submitted to a column loss.