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DEVELOPMENT OF MEMBRANAR EFFECTS IN FRAME BEAMS
Experimental and analytical investigations

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INTRODUCTION

Recent events such as natural catastrophes or terrorism attacks have highlighted the necessity to ensure the structural integrity of buildings under exceptional events. According to Eurocodes and some different other national design codes, the structural integrity of civil engineering structures should be ensured through appropriate measures but, in most of the cases, no precise practical guidelines on how to achieve this goal are provided. A European RFCS project called “Robust structures by joint ductility” has been set up in 2004, for three years, with the aim to provide requirements and practical guidelines allowing to ensure the structural integrity of steel and composite structures under exceptional event through an appropriate robustness.

The investigations performed at Liège University, as part of this European project, are mainly dedicated to the exceptional event “Loss of a column in a steel or steel-concrete composite building frame”; the main objective is to develop a simplified analytical procedure to predict the frame response further to a column loss. The development of this simplified procedure is detailed in two complementary PhD theses: the thesis of J.-F. Demonceau *[1]* and the thesis of H.N.N. Luu *[2]*. The present paper describes experimental and analytical studies carried out within the first PhD thesis *[1]*. In particular, a simplified analytical method allowing the prediction of the frame response with account of the membranar effects is described.

1 GENERAL CONCEPTS

The loss of a column can be associated to different types of exceptional actions: explosion, impact of a vehicle,… Under some of these exceptional actions, dynamic effects may play an important role; within the performed studies, it is assumed that the action associated to the column loss does not induce significant dynamic effects. So, the performed investigations are based on static approaches.

When a structure is losing a column, the latter can be divided in two main parts, as illustrated in *Fig. 1*:

- the directly affected part which represents the part of the building directly affected by the loss of the column, i.e. the beams, the columns and the beam-to-column joints which are just above the loss column and;
- the indirectly affected part which represents the part of the building which is affected by the loads developing within the directly affected part and which influences the development of these loads.

If a cut in the structure is realised at the top of the loss column (see *Fig. 1*), different internal loads in the vertical direction are identified:

- the shear loads V_1 and V_2 at the extremities closed to the loss column;
- the axial load N_{up} in the column just above the loss column and;
- the axial load N_{lo} in the loss column.

The objective of the performed studies at Liège University is to be able to predict the evolution of N_{lo} according to the vertical displacement of point “A” Δ_A, with due account to the eventual membranar forces developing in the structure, in order to know the requested ductility from the different structural members and to check the resistance of the indirectly affected part loaded by additional loads coming from the directly affected part.

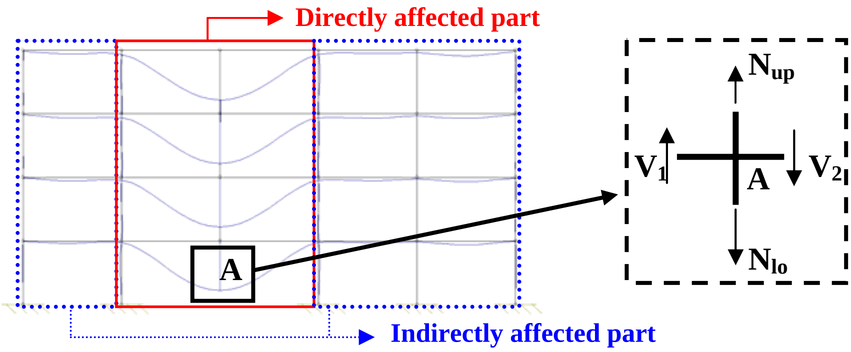

Fig. 1. Representation of a frame losing a column and main definitions

In *Fig. 2*, the curve representing the evolution of the normal load N_{lo} in the loss column (see *Fig. 1*) according to the vertical displacement Δ_a is illustrated:

- From point (1) to (2) (Phase 1), the design loads are progressively applied, i.e. the "conventional" loading is applied to the structure; so, N_{lo} progressively decreases (N_{lo} becomes negative as the column "AB" is subjected to compression) while Δ_A can be assumed to be equal to 0 during this phase (in reality, there is a small vertical displacement at point A associated to the compression of the columns below point "A"). It is assumed that no yielding appears in the investigated frame during this phase, i.e. the frame remains fully elastic.
- From point (2) to (5), the column is progressively removed. Indeed, from point (2), the compression in column "AB" N_{lo} is decreasing until reaching a value equal to 0 at point (5) where the column can be considered as fully destroyed. So, in this zone, the absolute value of N_{lo} is progressively decreasing while the value of Δ_A is increasing. This part of the graph is divided in two phases as represented in *Fig. 2*:
  - From point (2) to (4) (Phase 2): during this phase, the directly affected part passes from a fully elastic behaviour (from point (2) to (3)) to a plastic mechanism. At point (3), first plastic hinges are appearing in the directly affected part.
  - From point (4) to (5) (Phase 3): during this phase, high deformations of the directly affected part are observed and second order effects play an important role. In particular, significant catenary actions are developing in the bottom beams of the directly affected part.

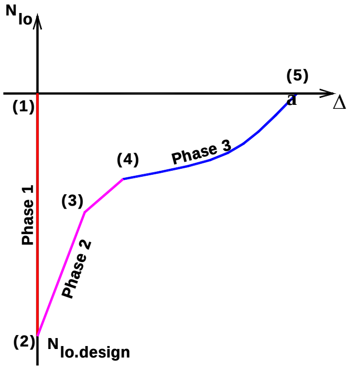

Fig. 2. Evolution of N_{lo} according to the vertical displacement at the top of the loss column

It is only possible to pass from point (1) to (5) if:

- the loads which are reported from the directly affected part to the indirectly affected part do not induce the collapse of elements in the latter (for instance, buckling of the columns or formation of a global plastic mechanism in the indirectly affected part);
- if the different structural elements have a sufficient ductility to reach the vertical displacement corresponding to point (5).

It is also possible that the complete removal of the column is reached (i.e. $N_{lo} = 0$) before reaching Phase 3.

The investigation of the response of the frame during Phase 1 and 2 is the topic of the thesis of H.N.N. Luu (*[2]* and *[3]*) while the response during Phase 3 is the subject of the thesis of J.-F. Demonceau *[1]*. The adopted strategy to study Phase 3 is presented in *Fig. 3*:

- Step 1: an experimental test is carried out in Liège on a substructure with the aim to simulate the loss of a column in a composite building frame.
- Step 2: analytical and numerical FEM tools are validated through comparisons with the experimental results
- Step 3: parametric studies based on the use of the models validated at step 2 are carried out; the objective is to identify the parameters influencing the frame response during Phase 3.
- Step 4: a simplified analytical method is developed with due account of the parameters identified at step 3 and validated through comparisons with the experimental test results of step1.

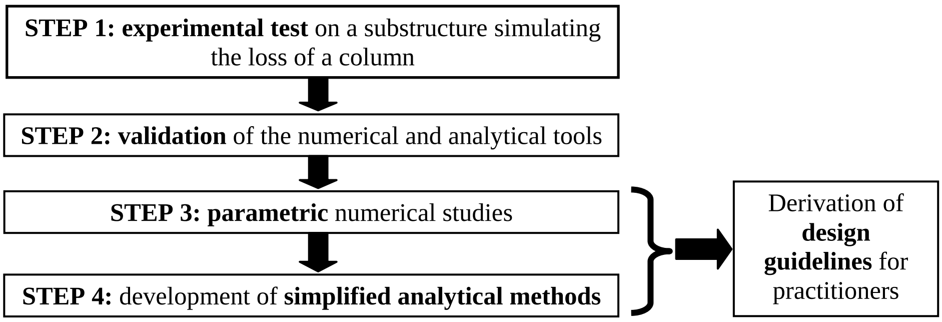

Fig. 3. Strategy followed at Liège University to investigate Phase 3

In the present paper, part of the investigations performed within steps 1 (*§ 2*), 2 (*§ 3*) and 4 (*§ 4*) are reflected. More information is available in *[1]*, *[4]* and *[5]*.

2 EXPERIMENTAL TEST ON A SUBSTRUCTURE

As previously mentioned, a test on a composite substructure has been performed in Liège to simulate the loss of a column. The main objective of the test is to observe the development of catenary actions within a frame and the effect of these actions on the behaviour of the semi-rigid and partial-strength composite beam-to-column joints. Indeed these joints are initially designed and loaded in bending, but have progressively to support tensile loads as a result of the development of membrane tying forces in the beams.

To define the substructure properties, an “actual” composite building has been first designed *[6]* according to Eurocode 4 *[7]*, so under “normal” loading conditions. As it was not possible to test a full 2-D actual composite frame within the project, a substructure has been extracted from the actual frame *[8]*; it has been chosen so as to respect the dimensions of the testing floor in the laboratory but also to exhibit a similar behaviour than the one in the actual frame. The tested substructure is presented in *Fig. 4*. As illustrated, horizontal jacks were placed at each end of the specimen so as to simulate the lateral restraints brought by the indirectly affected part of actual building when catenary actions develop.

A specific loading history is followed during the test. First, the vertical jack at the middle is locked and permanent loads are applied on the concrete slab with steel plates and concrete blocks (“normal” loading situation). Then, the vertical jack is unlocked and large displacements develop progressively at point A (*Fig. 4*) until the force in the jack vanishes (free spanning of 8 m). Finally, a downward concentrated vertical load is applied to the system above the impacted column and is then progressively increased until collapse. The “vertical load vs. vertical displacement at point A” curve is reported in *Fig. 5*.

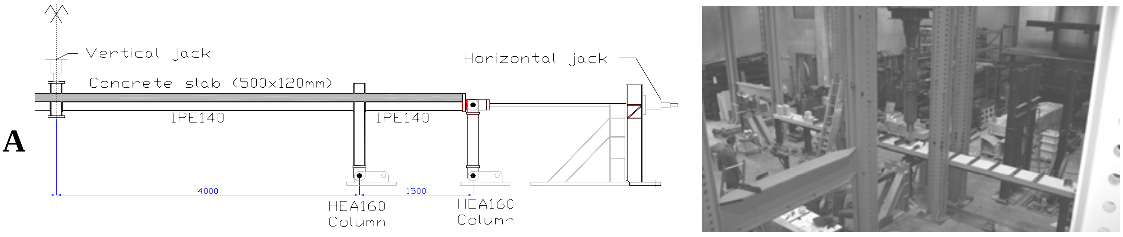

Fig. 4. Tested substructure

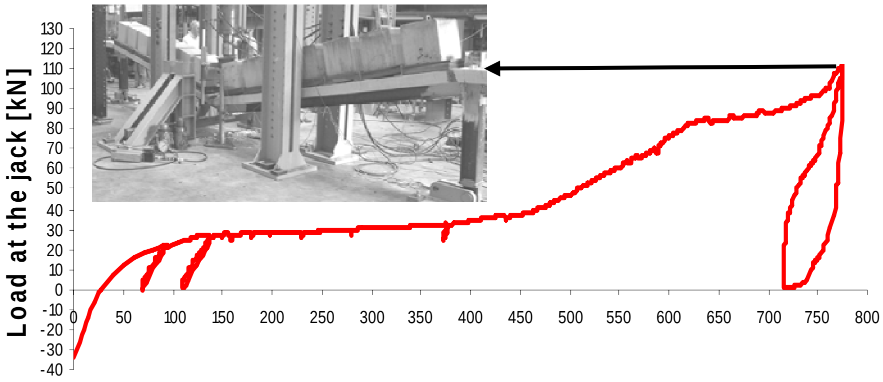

Fig. 5. “Vertical load at the jack vs. vertical displacement at point A” curve

Besides that, experimental tests in isolation have been performed at Stuttgart University on the composite joints of the substructure, respectively under hogging or sagging bending moments and tensile axial forces; finally tests on joint components have been realised at Trento University. So as to be able to compare the results obtained in the laboratories, all the steel elements (profiles, plates and rebars) were provided by the same companies and came from the same rolling. A unique chain of consistent experimental results is so obtained.

3 VALIDATION OF AN ANALYTICAL TOOL TO PREDICT THE COMPOSITE JOINT RESPONSE SUBJECTED TO COMBINED MOMENTS AND AXIAL LOADS

As previously mentioned, the structural joints during Phase 3 are subjected to combined bending moments and axial loads. In the PhD thesis of F. Cerfontaine *[9]*, an analytical procedure has been developed to predict the response of steel joints subjected to such loading. The proposed method is founded on the component method which is the recommended method in the Eurocodes for the design of joints subjected to bending moments.

In *[1]*, this method is extended to composite joints. The particularity of composite joint configurations is the fact that two main additional components are activated if compare to steel ones: the slab rebars in tension and the concrete slab in compression. As the analytical procedure presented in *[9]* is based on the component method concept, the latter is easily extended to composite joint configurations by including the behaviour of the two additional components into the procedure. However, the characterisation of the component “concrete slab in compression” is not yet available in the actual codes; accordingly, an analytical method to characterise this component in terms of resistance and stiffness is proposed and validated in *[1]*.

The extended method is validated through comparisons to results coming from experimental tests performed at Stuttgart University on the tested substructure joint configuration *[10]*. The comparisons are given in *Fig. 6*. On the latter, it can be observed that two analytical curves are reported:

- One called “plastic resistance curve” which is computed with the elastic resistance stresses of the materials and;
- One called “ultimate resistance curve” which is computed with the ultimate resistance stresses of the materials.

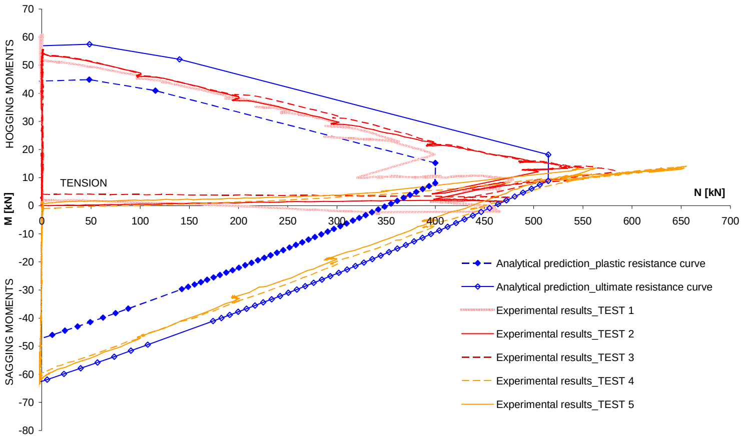

Fig. 6. Comparison of the resistance interaction curves

According to *Fig. 6*, the computed analytical curves are in very good agreement with the experimental results. Indeed, the experimental curves are between the plastic and ultimate analytical resistance curves what is in line with the loading sequence followed during the tests. The fact that the maximum tensile load reached during the experimental tests is higher than the one analytically predicted can be explained by membranar forces developing in some joint components in bending, forces which are not taken into account in the analytical method.

4 DEVELOPMENT OF AN ANALYTICAL TOOL TO PREDICT THE RESPONSE OF A STRUCTURE WITH ACCOUNT OF THE MEMBRANAR EFFECTS

Through numerical investigations *[1]*, it was shown that it is possible to extract a simplified substructure (see *Fig. 7*) able to reproduce the global response of a frame further to a column loss.

The objective with the analytical procedure is to predict the behaviour of the substructure in the post-plastic domain, i.e. after the formation of the beam plastic mechanism in the substructure; accordingly, the analytical model is based on a rigid-plastic analysis. Also, as the deformations of the substructure are significant and influence its response, a second-order analysis is conducted.

The parameters to be taken into account in the developed procedure are presented in *Fig. 7*:

- p is the (constant) uniformly distributed load applied on the storey modelled by the simplified substructure and the concentrated load Q simulates the column loss (= $-(N_{lo} - N_{up})$) (see *Fig. 1*) with N_{up} constant and equal to N_{up} at point 4 (see *Fig. 2*) what is demonstrated in *[2]*);
- L is the total initial length of the simplified substructure;
- Δ_Q is the vertical displacement at the concentrated load application point;
- δ_K is the deformation of the horizontal spring simulating the lateral restraint coming from the indirectly affected part;
- δ_{N1} and δ_{N2} are the plastic elongations at each plastic hinges;
- θ is the rotation at the plastic hinges at the beam extremities.

In addition, the axial and bending resistances at the plastic hinges N_{Rd1} and M_{Rd1} for the plastic hinges 1 and 4 and N_{Rd2} and M_{Rd2} for the plastic hinges 2 and 3 have also to be taken into account (it is assumed that the two plastic hinges 1 and 4 and the two plastic hinges 2 and 3 (see *Fig. 7*) have respectively the same resistance interaction curves).

In order to be able to predict the response of the simplified substructure, the parameters K and F_{Rd} have to be known; these parameters depend of the properties of the indirectly affected part (see *Fig. 1*). In *[2]*, analytical procedures have been defined to predict these properties.

The results obtained with the so-developed analytical procedure are compared to the substructure test results in *Fig 8*. In this figure, it can be observed that a very good agreement is obtained between the analytical prediction and the experimental results, what validates the developed method. More details about the developed method are available in *[1]*.

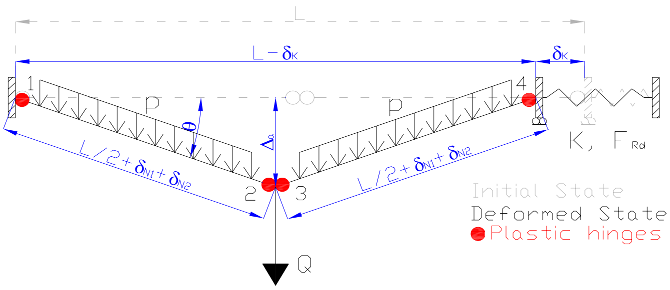

Fig. 7. Substructure to be investigated

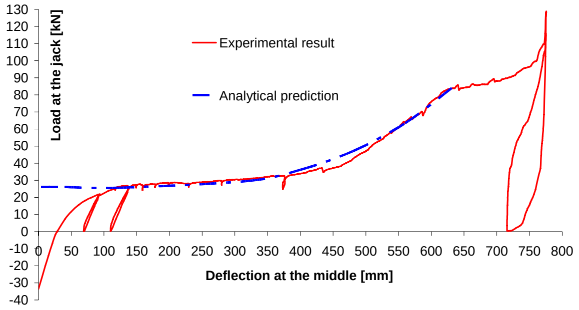

Fig. 8. Comparison analytical prediction vs. experimental results

5 CONCLUSIONS

Within the present paper, part of the experimental and analytical investigations performed in *[1]* is reflected. The general concept to study the behaviour of steel and composite frames further to the loss of a column has been first presented with a description of the followed strategy to investigate the development of the membranar effects within a structure. Then, the experimental test performed at Liège University on a substructure simulating the loss of a column in a composite building has been described. In addition, an analytical method to predict the behaviour of composite joints subjected to combined moments and axial loads has been presented. Finally, the analytical method allowing to predict the response of a structure when the membranar forces developed has been briefly described.

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