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Contribution to the derivation of robustness requirements for steel and composite structures

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Abstract

Recent events such as natural catastrophes or terrorism attacks have demonstrated 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 entitled "Robust structures by joint ductility" has been set up in 2004, for three years, with the aim to provide requirements and practical guidelines likely to ensure the an appropriate robustness to steel and composite buildings under exceptional events. In particular, one substructure test simulating the loss of a column in a composite building has been performed at Liège University. Present paper summarises first analytical, numerical and experimental investigations carried out at Liège University as part of this European project.

1. Introduction

A structure should be designed to behave properly under service loads (at SLS) and to resist design factored loads (at ULS). The type and the intensity of the loads to be considered in the design process may depend on different factors such as:

- the intended use of the structure: type of variable loads,…
- the location (region, altitude, …): wind action, snow, level of seismic risk,…
- and even the risk of accidental loading: explosion, impact, flood,…

In practice, these individual loads are combined so as to finally derive the relevant load combination cases. In this process, the risk of an exceptional (so totally unexpected) event leading to other accidental loads than those already taken into consideration in the design process in itself is not at all covered. This is a quite critical situation in which the structural integrity should be ensured, i.e. the global structure should remain globally stable even if one part of it is destroyed by the exceptional event. In conclusion, the structural integrity will be required when the structure is subjected to exceptional loads not explicitly considered in the definition of the design loads and load combination cases.

According to Eurocodes (prEN 1991-1-7, 2004, ENV 1991-2-7,1998) and some different other national design codes (BS 5950-1:2000, 2001, UFC 4-023-03, 2005), 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.

Even basic requirements to fulfil are generally not clearly expressed. Different strategies may therefore be contemplated:

- Integrate all possible exceptional loads in the design process in itself; for sure this will lead to non-economic structures and, by definition, the probability to predict all the possible exceptional events, the intensity of the resulting actions and the part of the structure which would be affected is seen to be "exceptionally" low.
- Derive requirements that a structure should fulfil in addition to those directly resulting from the normal design process and which would provide certain *robustness* to the structure, i.e. an ability to resist locally the exceptional loads and ensure a structural integrity to the structure, at least for the time needed to safe lives and protect the direct environment. Obviously the objective could never be to resist to any exceptional event, whatever the intensity of the resultant actions and the importance of the structural part directly affected.

In the spirit of the second strategy, a European RFCS project entitled "Robust structures by joint ductility – RFS-CR-04046" 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 events through an appropriate robustness.

The robustness is required from the structural system not directly affected by the exceptional event (to avoid the local destruction of the structural element where the event occurs being often not possible). In this process, the ability to redistribute plastically extra forces resulting from the exceptional event is of high importance. This requires from all the structural elements and from the constitutive joints a high degree of plastic deformability under combined bending, shear … or axial forces.

The partners involved in this previously mentioned project are:
- Stuttgart University, Germany;
- Liège University, Belgium;
- ProfilArbed-Research (PARE) from the ArcelorMittal Group, Luxembourg;
- PSP-Prof. Sedlaceck & Partner - Technologien, Aachen, Germany;
- Trento University, Italy.

Within this project, different exceptional actions are considered such as loss of a column in a building, loss of a bracing in a car park, unexpected earthquake, unexpected fire… The present article presents the developments performed at Liège University for the exceptional situation "loss of a column further to an impact" in an office or residential building.

2. Loss of a column further to an impact in an office or residential building

2.1 Followed strategy

The strategy followed at Liège University is illustrated in Fig. 1; it involves experimental, numerical and analytical aspects:
- Step 1: experimental tests are carried out by different partners in the project (see Section 2.2); in Liège, in particular, a test is performed 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 (see Section 2.3) through comparisons with the experimental results
- Step 3: parametric studies based on the use of the models validated at step 2 are carried out as described in Section 2.4; the objective is to identify the parameters influencing the frame response after the loss of the column or a bracing.

- Step 4: simplified analytical methods are developed (Section 2.5) with due account of the parameters identified at step 3; finally, these analytical methods are used to derive design guidelines for practitioners, what is the final objective of the RFCS project.

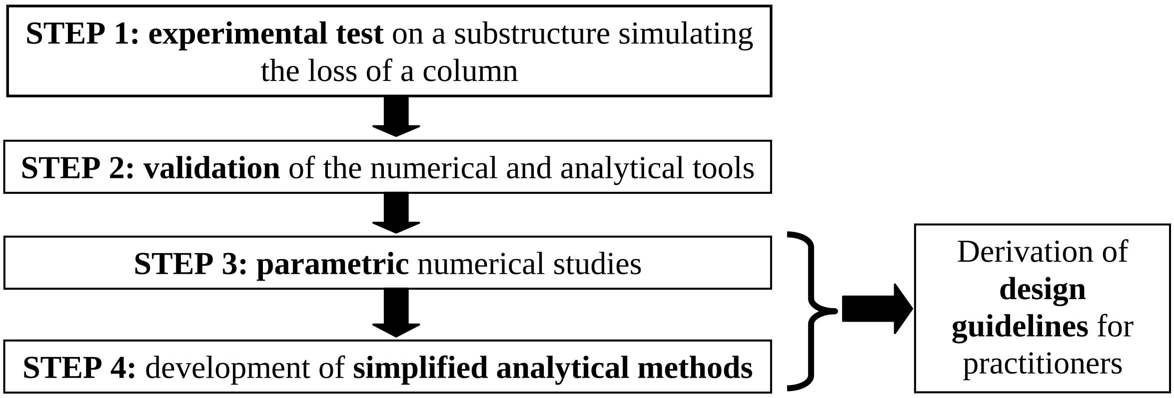

Figure 1. Strategy followed at Liège University

2.2 Experimental tests

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 (Demonceau and Jaspart, 2006a) according to Eurocode 4 (NBN EN 1994-1-1, 2005), 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 (Demonceau and Jaspart, 2006b); 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. 2. As illustrated, horizontal jacks were placed at each end of the specimen so as to simulate the lateral restraints brought by the undamaged part of actual building when catenary actions develop.

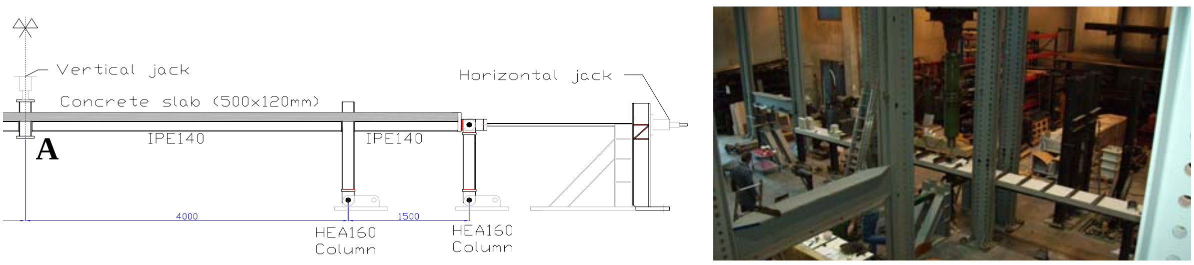

Figure 2. Tested substructure

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. 2) 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. 3.

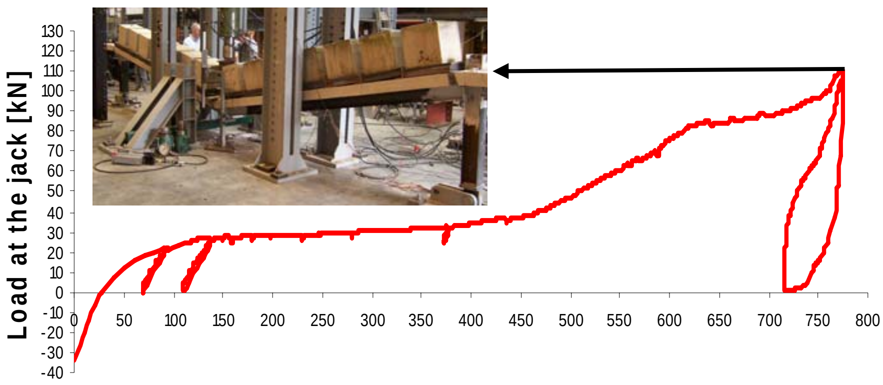

Figure 3. "Vertical load at the jack vs. vertical displacement at point A" curve

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.

2.3 Validation of the analytical and numerical tools

In order to validate the numerical and analytical tools used by the partners within the project, two actions have been initiated:

- validation through benchmark studies;
- validation through comparisons with experimental results.

The benchmark studies show a good agreement between the software used for the prediction of the frame response further to the loss of a column (Ansys for Stuttgart University, Abaqus for PSP in Aachen and the homemade FEM software Finelg for Liège University).

The validation of Finelg through comparisons with the substructure test results is in progress. Till now, the modelling of the substructure has been performed by considering the actual properties of the members and materials, but the response of the joints under bending moments only (from moment-rotation curves coming from the Stuttgart tests); the comparison between the numerical prediction and the experimental result is given in Fig. 4. It can be observed that Finelg is able to predict the formation of the beam mechanism but overestimates a bit the development of the catenary action in the substructure. It is due to the fact that the influence of the tensile loads on the response of the joints has not yet been introduced in the modelling. This will constitute the next step of the validation.

Also, in this part of the project, an analytical tool developed by Cerfontaine (Cerfontaine 2004) and dedicated to the prediction of the response of steel joints under bending moments combined to normal forces has been first extended to composite joints and then validated through comparisons to the experimental results obtained by Stuttgart University for the joint tests in isolation (see Fig. 5).

So, it can be concluded that validated numerical tools able to predict the behaviour of a impacted frame and an analytical tool for the prediction of the response of steel or composite joints under combined bending moments and axial forces are available.

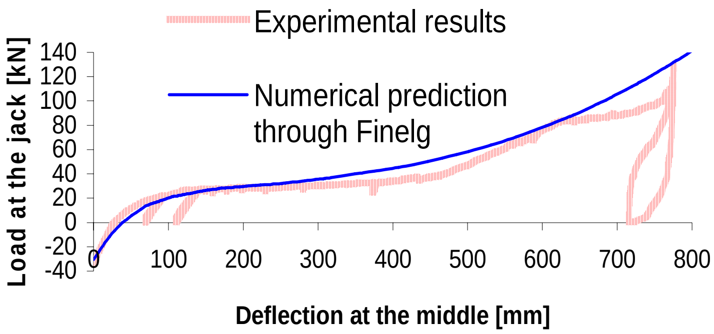

Figure 4. Substructure – numerical prediction vs. experimental result

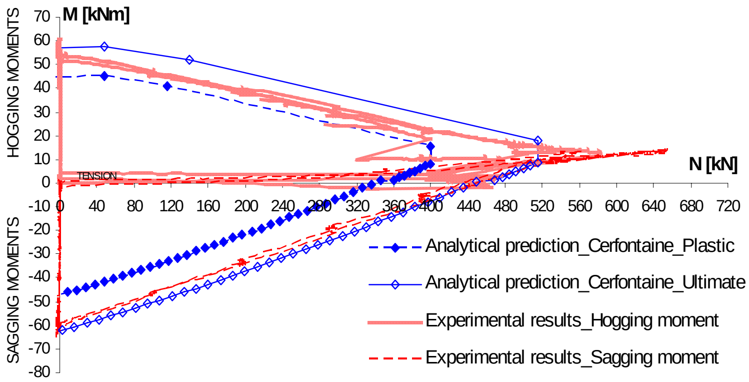

Figure 5. Joint in isolation - analytical predictions vs. experimental results

2.4 Parametric numerical studies

First a numerical study has been conducted by PSP in Aachen so as to demonstrate that it is possible to simulate the behaviour of the damaged part of the structure by a simplified two-beams subsystem, as illustrated in Fig. 6 where the horizontal spring simulates the restraint brought by the undamaged part of the frame (as in the experimentally tested substructure).

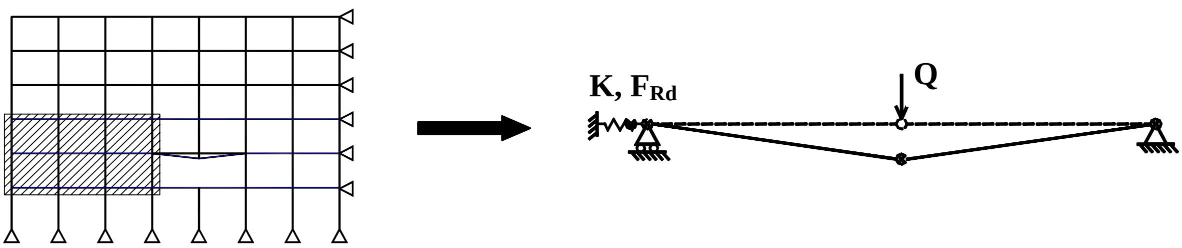

Figure 6. From an actual frame to a simplified two-beams subsystem

Then, so as to identify the main parameters influencing the response of the subsystem, intensive parametric studies have been performed in Liège on the simplified subsystem.

2.5 Development of simplified analytical methods

The first analytical developments deal with the “extraction” of the subsystem from the actual frame, what implies the definition of the lateral restraint K, the resistance F_{Rd} to membrane forces of the undamaged part of the frame and the load to be supported by the subsystem Q (with account of possible load redistributions within the frame further to the column loss). These developments are performed by Luu, a PhD student from Liège University.

The other analytical developments are aimed at predicting the response of the simplified subsystem, see Fig. 7, considering the main influencing parameters identified in Section 2.4.

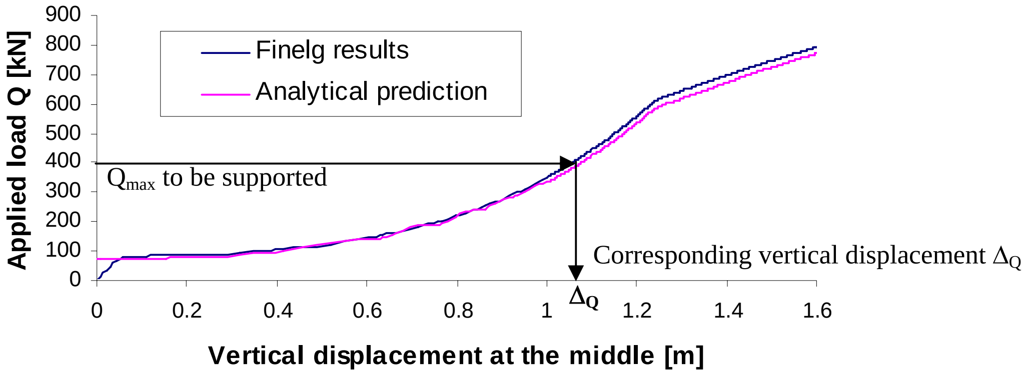

Figure 7. Analytical prediction of the simplified subsystem response

Through these developments, it is then possible, if the maximum load to be supported Q_{max} is known, to compute the corresponding vertical displacement Δ_Q and, from the latter, to compute the tying forces in the beams and the requested rotation capacity in the joints.

3. Conclusions

The present article summarises briefly the developments performed at Liège University in the field of robustness, in particular for the exceptional situation “loss of a column in a building further to an impact”. The followed strategy is first introduced and then, the experimental, numerical and analytical investigations are presented. These developments should lead soon to the derivation of requirements and design guidelines to ensure the robustness of buildings for the exceptional situation being here considered.

4. References

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