Robust structure by joint ductility

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Summary

In view of recent disasters and their immense economical and human consequences such as the flood catastrophe in South East Asia or the constant threat by international terrorism more and more focus is given not only on the safety of structures - to reduce the risk for the life of people by collapse even under exceptional loading – but on minimising the disastrous results and to enable a quick rebuilding and reuse.

One crucial mean to achieve this aim is the design of redundant robust structures. Robustness prevents the collapse of the total structure when only parts of the structure are damaged or destroyed. To avoid progressive failure, redundant structures with inherent sufficient ductile behaviour allowing deformations when a local failure occurs, have to be built.

Redundancy can be achieved by allowing force redistribution within a structural system. Therefore the single sections and joints have to be especially designed and optimised, not necessarily requiring additional fabrication costs. Steel is a preferable building material for robust structures because of its ductile properties. But until now no specific rules for robustness by ductile joints exist.

The aim of the present project is to define general requirements for ductile joints as part of a structural system subjected to exceptional unforseen loading.

Keywords: Robustness, ductility, joints, exceptional loading, progressive failure, redundancy

1. Introduction

The behaviour of steel and composite frames after failure of local structural elements caused by exceptional loadings (e.g. failure of a column caused by a vehicle impact, explosion, fire, earthquake, floods) is investigated. A progressive failure of the whole structure can be prevented by robust design. Robustness ensures structural safety by preventing the collapse of the total structure when only one part of the structure is damaged or destroyed.

This can be achieved by enabling the joints to provide large rotations, so that membrane forces can be activated allowing a redistribution of internal forces. Thus an adaptive structure is created which keeps sufficient strength even under exceptional loading and large deformations.

By increasing deformations joints are subjected to increasing tensile forces, while bending moment exposure of the joint decreases or is even inversed.

Within the research project various experimental investigations are made on the behaviour of the joints under large deformations and combined loading of bending and tension, including a full scale test of a substructure, joint tests and component tests.

The main objective of the project is to derive and develop simplified and economic design criteria allowing the designer to satisfy, in practical situations, the general requirement for robustness.

2. Concept and definitions

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 as the intended use of the structure (type of variable loads, ...), the location of the latter (region, altitude, ... which determines the wind, snow or seismic actions) and even the risk of accidental loading (explosion, impact, flood, ...). In practice, these individual loads are combined so as to finally define the relevant load combination cases.

In this process, the risk of an exceptional (and therefore 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 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 (explosion, impact, fire as a consequence of an earthquake, ...). 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 of the load combination cases.

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. 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 a 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 present project the second strategy is intended to be followed.

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.

As a general procedure to derive robustness requirements, different structural systems subjected to exceptional events are numerically investigated in order to see how the structures work when part of the structure is destroyed as well as how and how far redistribution takes place. From these investigations, extreme situations related to the destruction of a part of the structures (one column, two columns, one beam, ...) are identified. One of these in particular, the loss of a column, is intended to be tested experimentally; this will allow to validate the numerical tools used in the preliminary study. Finally, parametrical studies will be carried out numerically for the selected events and simple analytical models will be developed so as, at the end of the project, to be able to derive robustness requirements.

Practically speaking now, many exceptional events could be considered, but only the following ones are covered by the present project:

- loss of a column in an office or residential building frame;
- loss of a beam in an office or residential building frame;
- loss of a column in an industrial portal frame;

- loss of a bracing in an industrial portal frame;
- loss of a bracing in a car park;
- Unexpected earthquake;
- Unexpected fire.

For the five first cases, FEM numerical simulations will be carried out. In this process, a special attention will be devoted to the study of the loading sequence inside the joints. As a result of these FEM numerical simulations and associated parametrical studies, simplified behavioural models will be developed and validated; these should progressively lead to analytical models, from which requirements to be satisfied by the structural system and by the joints will be derived. Progressively other exceptional situations will be investigated in the same way and related design requirements will be derived. Possibly similarities between different exceptional events and their corresponding failure modes will be identified and more general requirements are so expected to be formulated. For the six and seventh here-above listed events, the work consists in expressing requirements that structures which have not been explicitly designed for fire and/or seismic actions should fulfil so as to possess a certain amount of robustness against such unexpected extreme situations. In different countries, "good practice" recommendations and conceptual design guidelines exist (for instance for so-called "non-engineered structures") and the work should therefore consist in gathering and analysing this available material and present it in an adequate format.

3. Experimental investigations

3.1 Overview and fabrication

An adjustment of the component tests, the joint tests and the substructure test conducted by various partners is very important to get comparable results. Therefore a benchmark model for the experimental investigations has been defined.


Fig. 1 *Column specimens*


Fig. 2 *T-stub specimens*

At the University of Liège a composite frame has been designed according to prEN 1994-1-1 [3]. The loads are taken as recommended in EN 1991-1-1 [4]. Thus a building composed of three main frames, with a height of three storeys and with a space of 3 m between the frames has been chosen. The span of the beams is 4 m so as to be in line with the dimensions of the substructure which will be tested in Liège; these dimensions are limited according to the laboratory facilities. The partners further agreed that the experiments should form a unique chain in order to get consistent results. This means the joints tested in Stuttgart are part of the substructure test conducted in Liège, as well as the component tests of Trento include all components which are relevant within the joint and substructure tests. In addition to that intensive coordination covering the fabrication of the testing bodies is necessary. Profiles and plates will be used of one rolling. The reinforcement for the testing bodies is ordered together using reinforcement bars of one rolling for each diameter.

The first specimens for the component tests in Trento are already fabricated and in Fig. 1 and Fig. 2 some testing bodies are shown.

3.2 Component tests

The experimental study of joint response has been designed following the philosophy of component approach. At this aim, tests on the main components of the sub-structure to be tested in Liege have been planned with the main purpose of investigating their deformation capacity and ultimate strength. With reference to Figure 3, which is related to an internal joint of the sub-structure, tests have been planned on both the reinforced concrete slab and the steel joint components. Additional tests are considered in order to evaluate the performance of the steel connection as a whole. Further tests to explore the sensitivity of the T-stub components to significant parameters have been designed.

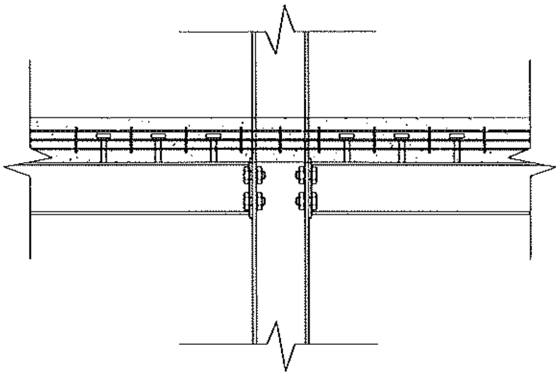


Fig. 3 *Internal joint of the sub-structure*

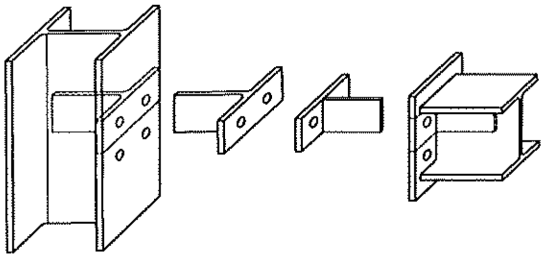


Fig. 4 *T-stub specimens*

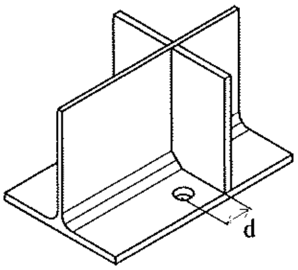


Fig. 5 *Stiffened T-stub specimen*

In detail, the experimental study comprises of:

1- Pure tension tests on four reinforced concrete slabs (length 3.7 m, width 0.5 m, thickness 0.12 m) up to the fracture of the re-bars. The results of recent studies [1] confirmed the beneficial and non-negligible contribution of tension stiffening on the performance of composite joints and pointed out the need of detailed analysis of this effect with particular reference to the large displacements field. In order to analyse the influence of the reinforcement ratio on tension stiffening, six additional tension tests are included, planned on specimens with square cross section (side of 0.22 m). Two reinforcement ratios, $\rho_1 = 0.831\%$ and $\rho_2 = 0.415\%$, are considered. The former reinforcement ratio is equal to that of the slabs;

2- T-Stub specimens simulating the column and the end-plate components (Fig. 4). A total of 42 tests on T-stubs reproducing the actual dimension of the joint (Fig. 4) will be performed. T-stubs will be tested under pure tension as well as under different combinations of shear (V) and axial force (T). The results should enable predetermination of interaction V-T. Furthermore, tests on T-stubs of length greater than the effective length in accordance to Eurocode 3 Part 1-8 [2] are planned. These second series of tests on T-stub seems necessary to investigate the reliability of the equations proposed by Eurocode 3 Part 1-8 [2].

3- Stiffened T-stub specimens. Tension tests are designed in order to evaluate the influence of stiffeners on the T-stub performance. The longer T-stub configurations of the second series, with stiffeners (Fig. 5) are considered. Three different relative positions between the bolts line and the stiffener (distance d in Fig. 5) were adopted for a total of 24 tests.

4- Connection tests aim at studying the complete steel joint response. Three test configurations enable investigating the performance of the:

- end-plate T-stub connected to the column under tensile load;
- full steel connection (beam and end plate) on rigid support subject to tension or compression force;
- complete joint (including beam and column stubs) under tension or compression.

3.3 Joint tests

The joint tests planned at the University of Stuttgart can be subdivided into two main series. One series on composite joints with dimensions and design related to the substructure test in Liège, and a second series bending tests on pure steel joints.

The tests on composite joints mainly investigate the behaviour of the joints under combined loading. Special focus is given on the load path. The joints will undergo a change from pure bending exposure to combined bending and tension exposure.

For the combined bending and tension tests the following test procedure will be applied to the composite joints:

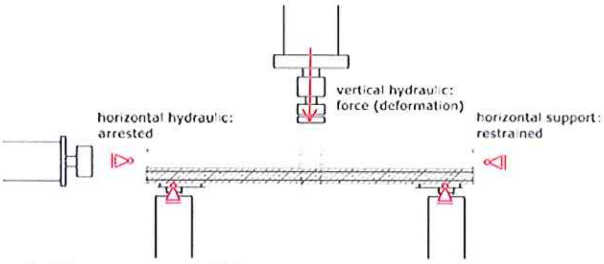


Fig. 6 *First stage of the composite testing procedure*

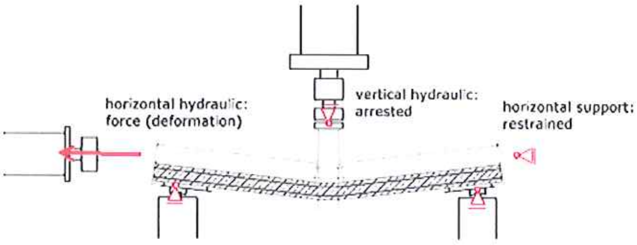


Fig. 7 *Second stage of the composite testing procedure*

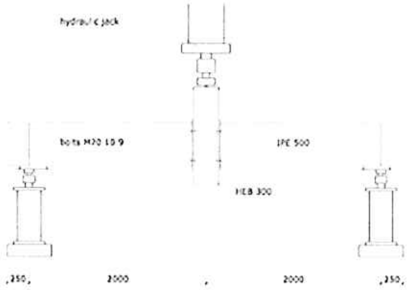


Fig. 8 *second testing series: pure steel joints*

As given in Figure 6 before any loading of the vertical hydraulic jack is applied, the horizontal jack and the horizontal support are restrained. By increasing force and deformation by the vertical hydraulic jack a moment is applied to the testing specimen. Due to the restrain of the horizontal supports axial forces will build up. The deformation of the testing body is increased beyond a moment just below the ultimate moment of the joint Mj,u until a predefined rotation of the joint. After reaching the predefined joint rotation the vertical jack is arrested in order to keep the rotation of the joint as presented in Figure 7. By the horizontal hydraulic jack a tensile force is applied on the testing body, leading to a decreasing moment exposure of the joint. The first test series comprises five composite joint tests. Two joints under bending and tension for the hogging moment (concrete slab in tension), one joint under bending and tension for sagging moment (concrete slab in compression) and two pure bending moment testss for reference. The tensile forces applied to the testing specimen will be increased up to failure.

The bending tests on pure steel joints include a number of six tests. The longitudinal dimensions of the testing body and the principal test set-up can be taken from Figure 8. The beams of the testing specimen consist of IPE 500 profiles, while for the column an HEB 300 profile is used. The bolts are M20 of grade 10.9. The endplate dimensions and the thickness are varied. All steel elements consist of S355.

The aim of the pure steel joint tests on large IPE 500 profiles with thin endplates is to analyse the ductility criterion for steel joints given in EN 1993-1-8 [2]. In previous tests conducted in Stuttgart by Kuhlmann/Schäfer [1] brittle failure of the bolts has been observed although the ductility criterion according to EN 1993-1-8 [2] was not violated. It is assumed that the brittle bolt failure occurred due to bending exposure of the bolts. This bending exposure seems to depend on the distance between the flange and the web of the beam on one hand side and the bolt on the other side. To receive a more reliable criterion in order to prevent premature brittle failure modes these tests will be conducted.

3.4 Substructure test

The aim of this test to be performed at Liège University is to investigate the behaviour of a composite building frame under an exceptional event resulting in the loss of a column.

First an "actual" composite building has been designed according to the EC4 [3] recommendations, so under "normal" loading conditions (i.e. loads recommended in Eurocode 1 [4] for office buildings). And as it was not possible to test a full 2-D actual composite frame within the present project, a substructure has been extracted from the full frame.

The substructure has been chosen so as to respect the dimensions of the testing floor but also to exhibit a similar behaviour than the one of the actual frame. In reality, it corresponds to the lower storey of the full composite frame (Fig. 9). But as the dimensions of the testing floor in the laboratory is limited, the length of the end beams is somewhat reduced as illustrated in Figure 9.

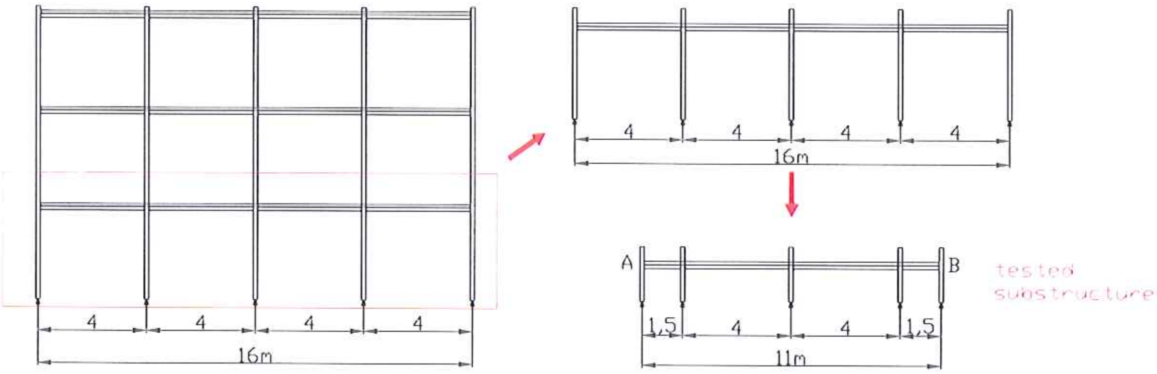
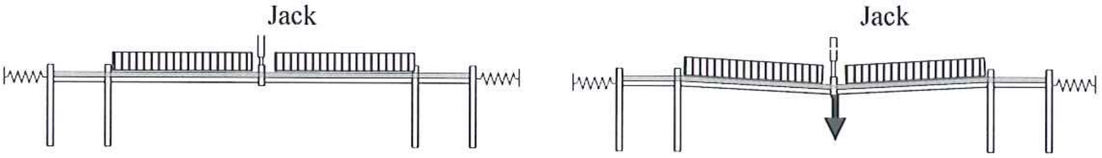


Fig. 9 *From the actual frame to the tested substructure*

The intended load sequence during the test is the following:

- The substructure is first loaded with an uniformly distributed load on the internal beams, in accordance with what is applied in the actual building (Fig. 10a); during this loading, the jack is locked (so simulating the action of the not yet impacted column).
- In a second step, the support brought by the jack is removed by unlocking the jack; thus large deformations and rotations of the testing body can be expected. The procedure continues then by applying a downwards vertical force on the system with the jack, so creating further deformation (Fig. 10b).



a - Uniformly distributed load *b- Unlocking of the jack and further vertical loading*

Fig. 10 *Load sequence on the substructure*

The test results will be used to validate the FEM approaches used later on in parametrical studies and will also be of high interest to validate the design of the composite joints based on the use of Eurocode 4 [3] recommendations and on the expertise of the research partners resulting from previous studies on composite joints.

4. Numerical investigations

The numerical investigations contain calculations on a simplified level and calculations on a sophisticated level. The main difference between the system calculations on the different levels is the degree of the modelling. Both calculation levels perform 3D calculations but the calculations on a sophisticated level include effects like post plastic behaviour and strain hardening while the simplified calculations are carried out on the basis of the more simple Eurocode 3-1-8 [2] models.

For the calculation on a simplified level the following simplifications have been made, in order to make sure that the main influencing parameters can be identified:

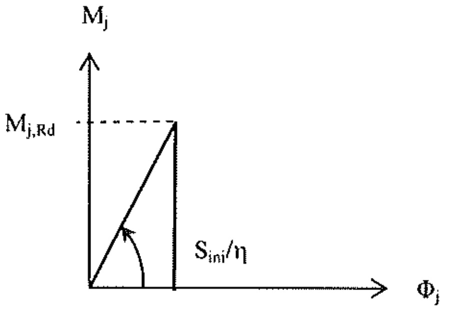


Fig. 11 *M-Φ-curve acc. to EC3-1-8 for brittle failure*

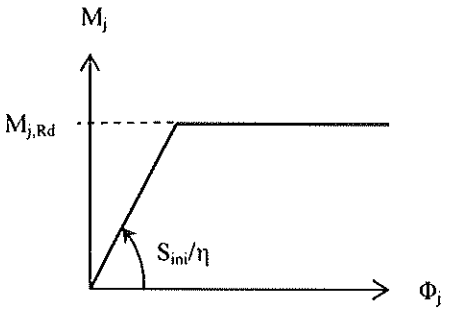


Fig. 12 *M-Φ-curve acc. to EC3-1-8 for ductile failure*

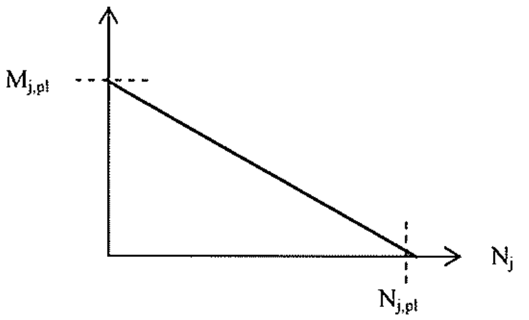


Fig. 13 *Linear M-N-interaction according to EC3-1-8*

Moment resistance, axial resistance and the initial stiffness of the joints shall be calculated according to EN 1993-1-8 [2] and the ECCS Doc. 109 (1999) [5]. Thus a bilinear relation between moment and rotation of the joints will be used. For brittle failure modes a sudden decrease after reaching the moment resistance of the joint $M_{j,Rd}$ is assumed, pictured in Figure 11. For joints with a ductile failure it is assumed that they are able to keep their moment resistance $M_{j,Rd}$ until the rotation capacity is reached, given in Figure 12. In a first approach it is assumed that the rotation capacity is large enough to allow membrane forces to develop which cause due to the M-N-interaction a decrease of the bending moment in the joint. Thus however no explicit number for the rotation capacity is yet given. It will rather be one of the results to gain required rotation capacities, and compare them afterwards with experimental results or more advanced calculation methods. The M-N-interaction will also be assumed as given in the code by a linear interaction, shown in Figure 13. Another simplification partners agreed to concerns the modelling of the material behaviour. For first approaches only bilinear behaviour of the steel and the reinforcement will be accounted for, while in a second step more sophisticated strain stress relations might be applied.

The second step are the calculations on a sophisticated level. They include modifications and extensions of the simplified models and consider non-linear characteristics of the joints. The analysis can be refined by input of the experimental test results. So it is possible to get a comparison of the ductile deformation of the joints: numerical studies vs. experimental tests. By benchmarking the FE-models with the test results a very realistic FE-model is gained. With this FE-model the aims of the calculation on a sophisticated level can be followed up:

- analysis of structural systems concerning robustness
- detection of the parameters influencing robustness (parameter study)
- optimisation and idealisation of the joints to obtain robust structures

5. References

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6. Conclusions and Outlook

Progressive failure of the whole structure caused by local damage (e. g. failure of a column caused by a vehicle impact, explosion, fire, earthquake) can be prevented by robust design. Profiting from the inherent ductile behaviour of steel, this project analyses the requirements for robustness and develops new ductile joint solutions to allow for a force redistribution within the structure so that a global collapse of the building is prevented and structural safety is ensured. Criteria for robust structures, especially concerning steel and composite joints are elaborated and illustrated by drawings in a handbook for easy understanding and realisation by the constructor.

The aim is to obtain robust structures by one small additional effort because mainly the inherent reserves of the structural system will be made available for practical design no additional elements are needed to achieve redundancy.

To identify requirements for structures which originally have been designed for "normal" load combinations to behave robust under unexpected exceptional loadings leads to a new view on structural safety which may be transferred to others than steel frame structures.

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