SDSS'Rio 2010 STABILITY AND DUCTILITY OF STEEL STRUCTURES
E. Batista, P. Vellasco, L. de Lima (Eds.)
Rio de Janeiro, Brazil, September 8 - 10, 2010

ROBUST DESIGN –ALTERNATE LOAD PATH METHOD AS DESIGN STRATEGY

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Keywords: Robustness, robust design, alternate load paths, ductility, composite joints, catenary action

***Abstract**. The paper highlights the ductility demand of beam-to-column connections in the frame of progressive collapse assessment of steel or composite structures considering sudden column loss. For progressive collapse mitigation different design strategies are available to increase the collapse resistance of a building. A very effective design strategy in buildings is the provision of alternate load paths. Besides strengthening the structural system alternate load paths could be also realized by allowing change of bearing mechanism within the structural elements. Therefore the structural system has to undergo large deformations resulting in high demands on ductility of members and joints. The ductile joint configurations, presented within this paper, allow for redistribution of internal forces within the structural system by enabling large deformations. So they are contributing to the redundancy of steel or composite frame structures due to their beneficial properties concerning ductility supply, the possibility to activate plastic reserves as well as energy absorption capacity.*

1 INTRODUCTION

Depending on the public or commercial relevance of a building today it is no longer sufficient for engineers to consider only basic design criteria for planning of structural framework. Engineers are increasingly required to consider progressive collapse mitigation as additional design criteria. For building structures the design strategy of alternate load path is therefore quite effective. The alternate load path method is realized for that matter by activating plastic system reserves and by transition from flexural loading to membrane tensile action in the members and joints initiating of catenary action. Therefore the joints have to be designed in detail and all single joint components have to be adjusted in such a manner that under bending and tensile loading at each time of loading the weakest component has to be always ductile. This is feasible with only small additional effort by using the inherent plastic reserves of the material steel.

2 ALTERNATE LOAD PATH METHOD

2.1 General

The definition of robustness as given in EN1991-1-7 [2] refers to limiting local failure to such an extent that no disproportionate collapse occurs. Such a general statement of robustness is very close to the definition of the concept of collapse resistance. Collapse resistance has to be provided to ensure the mitigation of progressive collapse. Robustness as characteristic of the load-bearing structure is thereby of special importance. A robust structure is at the same time collapse resistant [12].

Increasing the redundancy of the structure by well designed alternate load paths is advantageous if local failure is accepted and limitation of the collapse of the remaining structure is required. Therefore the structure has to be designed to be able to redistribute the loads from the damaged part into the undamaged part by avoiding at the same time a propagation of the collapse disproportional to the initial failure.

Particularly in cases in which collapsing parts cause impact loading on key elements. Designing for such high impact loads is, in most cases, not possible. Such conditions are particularly found in structures of primarily vertical alignment, such as buildings structures.

2.2 Redundancy as robustness measure

In order to be effective as robustness measure alternate load paths have to be designed sufficiently strong to transfer the actual occurring forces, including e.g. over-strength effects. An alternate load path may on the one hand be formed within the structural system (global level) by e.g. strengthening of transfer girders or by bracing a full floor level to suspend the loads above the damaged part like an outrigger, see Figure 1a. On the other hand redundancy can be achieved by allowing force redistribution within a structural member (local level). Structural steel and composite buildings with inherent sufficiently ductile material behavior allow large deformations when local failure occurs. Large deformations result in large plastic strain rates of material which enables the activation of additional plastic material reserves. So on local level the material steel has the capability to form plastic hinges which all activating also plastic system reserves by redistributing. On global level the redundancy of steel structures for progressive collapse mitigation may form alternate load paths. e.g. by activation of catenary action in the horizontal members that means by transition from flexural loading to membrane tensile acting in the members and joints, see Figure 1b. Therefore a highly ductile behavior of all structural members combined with sufficient strength is necessary. In framed structures the joints are in general the weakest link and therefore special focus is on the joint design to avoid a premature failure of the connections during the procedure of force redistribution.

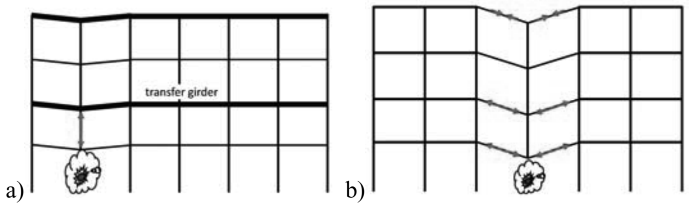


Figure 1: Alternate load paths by a) strong transfer girders or b) catenary action

Steel and composite members benefit from the ductile material behavior of structural steel. So steel has the capability to combine strength, ductility and energy absorption capacity which are basic properties for designing robust and redundant buildings.

Plastic material reserves of steel depend on the distance between the level of the nominal values and the actual values as well as on the ratio of f_u/f_y. In a structural robustness analysis the actual material properties are of main interest. Information about actual material resistance of steel is e.g. available in the probabilistic model code of the Joint Committee of Structural Safety [6].

2.4 Ductility demands for members and joints

For common steel profiles in structural engineering depending on the rotation capacity of the cross-section diverse categories of ductility classes exist. So the capability of the cross-section to undergo locally a total plastification i.e. to develop a plastic hinge and to assure additionally sufficient rotation capacity without premature stability failure (class 1 cross-section) is ensured by slenderness limits of cross-sectional parts. Therefore for plastic analysis of a steel structure including redistribution the requirements according the various codes are to use only those cross-sections with sufficient moment bearing capacity as well as rotation capacity. If rigid and full-strength joints are used the plastic hinges are located in the beams. So the total required deformation and rotation capacity to activate the membrane effect in the direct affected part of the structure has to be offered by the beam members. But full-strength joints cause much additional effort and they are costly.

Ductility demands for joints are decisive for partial-strength joints which have less resistance than the beams but also reduced fabrication costs compared to full-strength joints. Using partial-strength joint configurations the plastic hinges are developing initially in the joint which requires high rotation capacities of the joints. Therefore a detailed joint design is necessary considering the interaction of all joint components including over-strength effects to ensure that for the whole loading sequence of the joint the decisive weakest component is always ductile, see also chapter 4.

For bolted connections there is interplay of hardening or over-strength effects and the various deformation capacities of the single components. By ensuring that especially the components “endplate in bending” and “column flange in bending” have a certain ductility additional membrane effects on local level (in the T-Stub) may be activated leading to a further increase of the resistance provided there is sufficient bearing capacity of the bolts.

3 REDUNDANCY OF DIFFERENT SLAB SYSTEMS

In steel-concrete-composite structures the choice of the slab system not only influences the erection time and building costs but also the redundancy of the global structure or the structural robustness as characteristic of the structural system. Depending on the slab design, for exceptional load cases like column loss either 3D-behavior or only 2D-behavior is available.

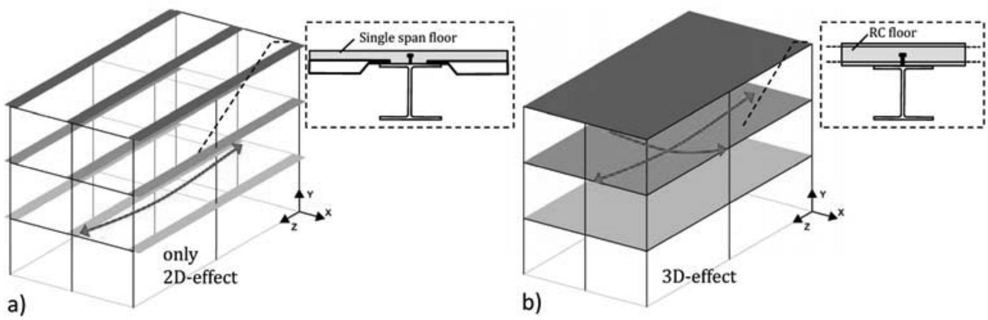


Figure 2: Composite frame under the event column loss with a) 2D-effect and b) 3D-effect

For framed composite structures without a continuous slab (floor system as single spans with only minimum reinforcement) the single slabs are not transversely tied together. For this reason in case of column loss the membrane action may only be activated in plane of the directly affected frame. So only the composite main beam system is able to redistribute forces and offer alternate load paths.

The slab in this case is unable to activate additional membrane effects transversally to the frame plane. So only 2D-behavior may be assumed within a large displacement analysis, see Figure 2a.

Having a continuous RC slab in the composite structure including a uniform amount of reinforcement the slab is connecting the single frames transversally. Consequently for the event of column loss the slab is not only contributing to the resistance of the composite beam in the plane of the directly affected frame but also acting as a tie in transversal direction. The RC slab provides ties in two horizontal directions and enables therefore 3D-behavior for the case of column loss (see Figure 2b). However, for effective operation the continuity and anchorage of the ties is obligatory. Activating membrane action in longitudinal direction within the composite beams and joints and additionally in transversal direction within the RC slab the redundancy of the composite frame is clearly increased in comparison to 2D systems.

4 STRUCTURAL JOINT DESIGN

4.1 General

For partial-strength joint solutions highly ductile joint behavior is especially important due to the fact that the plastic hinge is located in the joint and all global deformations have to be realized mainly by joint rotation/deformation. Therefore the joints are the decisive link in the structure and their resistance and deformability define the global redundancy of the structure. In comparison to nominally pinned joints there are only small extra costs (material + labor) but much more redundancy of the structure, so by only small additional efforts the effectiveness concerning progressive collapse mitigation is improved [10].

4.2 Design of the steel elements of the joint

For the design of pure steel joints or for the steel elements of composite joints the adjustment of the single joint components is of high importance in order to design highly ductile joint configurations. Therefore the parameters mainly influencing the joint behavior have to be treated with special care. Table 1 describes the qualitative degree of influence concerning the rotation capacity as well as the bearing capacity of the various parameters investigated for the joint components. So small changes of some of these parameters might positively influence the ductility of the joint in a significant way whereas at the same time the bearing capacity is only decreasing marginally. The listed parameters are mainly influencing the components "endplate in bending" and "column flange in bending" which are able to activate additional local membrane effects under large deformations. So local additional bearing effects may compensate the decrease of the joint bending capacity when reducing e.g. the endplate thickness or the steel grade.

Table 1: Qualitative influences of main steel joint parameters

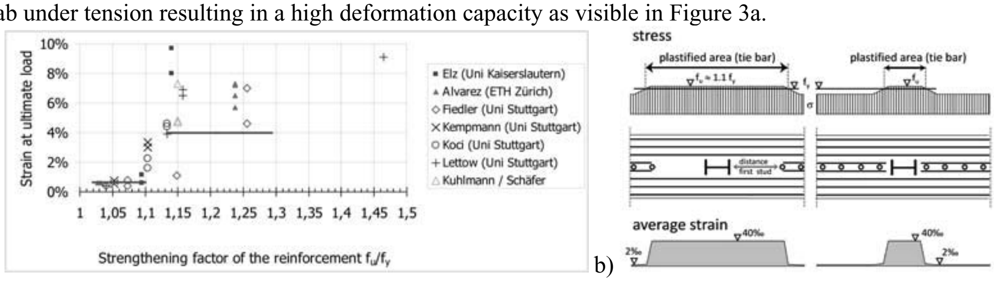
Parameter	influence on rotation capacity	Influence on bearing capacity
ratio $d_{bolt}/t_{endplate}$	+	-
bolt arrangement	+	-
steel grade endplate	+	-
ratio $t_{endplate}/t_{column\ flange}$	o	n.n
+ disproportionate high	o proportionate	- little

4.3 Design of the concrete slab in a composite joint

By adding a reinforced concrete slab and shear connectors to the pure steel joint a composite joint is obtained. To get also a highly ductile behavior for the composite joints the tension bar in the slab in the hogging moment region should be designed with high deformation capacity. Thus the reinforcement within the joint region should be able to undergo high plastic strains. As meshed reinforcement has a negative influence on the deformation capacity only steel rods should be used. Furthermore the following parameters are influencing significantly the available extension in the slab:

- class of reinforcement
- reinforcement ratio
- and arrangement of shear connectors

According to EN 1992-1-1 [3], Annex C there are three classes of reinforcement A, B and C in which class C (seismic steel) is the most ductile one in terms of maximal available strain and high ratio of f_u/f_y. For class C the ratio f_u/f_y is higher than 1.11, which is relevant for high available strains of the reinforced slab under tension resulting in a high deformation capacity as visible in Figure 3a.



a) b)

Figure 3: a) Influence of ratio f_u/f_y for the available ultimate strain of a reinforced concrete bar in tension, b) Influence of stud and reinforcement arrangement in the hogging moment zone of the slab [11].

The reinforcement ratio is influencing the moment resistance and the deformation/rotation capacity of the joint. By increasing the amount of reinforcement the deformation capacity is also increased. The reason is that the reinforcement ratio is significantly influencing the steel stress σ_{sr1} of the rebar when a first crack has formed. The ratio of σ_{sr1}/f_{yk} is important for the available plastic strain ε_{smu} of the reinforced concrete slab under tension, where f_{yk} is the yield strength of the rebars. For high deformation capacities of the slab a higher reinforcement ratio is advantageous because a rising ratio causes steel stresses σ_{sr1} when a first crack has formed which are well below the yield strength.

Beside the reinforcement ratio and class the arrangement of the shear studs in the hogging moment region are influencing the deformation capacity of the slab. More precisely the distance of the first shear stud to the column profile is decisive for the available expansion length of the rebars. By increasing the distance of the first stud the length for activating plastic strain in the reinforcement is clearly increased resulting in increase of deformation capacity. It is pointed out that also a discontinuous amount of reinforcement within the "tension bar" in the joint region should be provided to profit from the modified stud arrangement, see Figure 3b.

4.4 Over-strength effects

According to the basic design criteria (ULS + SLS) members and joints are designed assuming nominal material values. This is justified by the present safety concept. However for large displacement analysis considering only nominal values may lead to results which are non-conservative.

So aside of the plastic behavior of the material and the stability sensitivity of the sections which dominate the ductility of the members the joint behavior is decisive. Composed of various components the aim should be that only ductile components control the overall joint behavior. For this not only the component behavior itself is of importance but the interplay of the various components considering also possible over-strength effects play an important role.

Figure 4 gives the example of a joint composed of a ductile and a brittle component, e.g. the endplate in bending acting together with bolts which usually fail in a brittle manner. The design according to the nominal values of strength leads to a moment rotation curve of the joint also acting ductile, see case a). However the actual values of strength may exceed the nominal values (over-strength effects) so that no longer the ductile component dominates the failure load, but the brittle one, see case b). As a consequence the overall behavior of the joint shows a very limited rotation capacity. Disregarding over-strength effects the joint may lead to only limited ductility as shown and as consequence no redistribution of forces can take place that means the structure has only reduced redundancy.

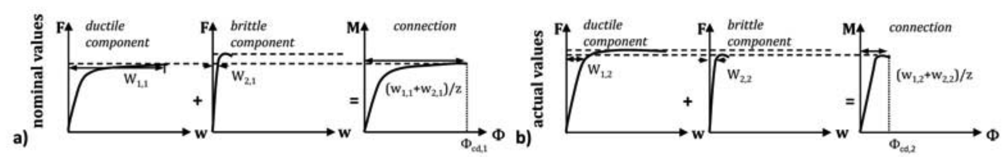


Figure 4: Influence of over-strength effects on the rotation capacity

5 EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON JOINTS

5.1 General

The European RFCS research project Robustness [8] recently finished has carried out extensive experimental and theoretical investigations on the behavior of steel-composite joints under biaxial loading, especially concerning the joint ductility to create robust structures which are able for load redistribution under exceptional loading and are insensitive to progressive collapse. It has demonstrated that the former concept to strengthen the joints in order to achieve that the plastic hinges appear in the beams is not a necessary condition for activation of catenary action in a frame structure for the design strategy of alternate load path method, but that it is also possible to place the plastic hinges into the joints by designing partial-strength joints with sufficient ductility. Within a national research project [9] parameters influencing the ductility of bolted beam-to-column connections were investigated. Furthermore the influence of over-strength effects on the resistance and rotation capacity of the joint was analyzed. In a current diploma thesis [7] a composite structure is analyzed for the event column loss.

5.2 Experimental investigations

Within the two mentioned research projects the joint deformability and ductility as well as the combined bending and tensile resistance have been investigated.

The performed steel joint tests mainly aimed at the investigations of increasing the joint ductility by varying different parameters. The main parameters influencing the deformability in the tension zone of the joint are the ratio of the endplate thickness and the bolt diameter (under consideration of the individual material strength) and the arrangement of the bolts depending on the distance to the web, see Table 1.

By decreasing the ratio of the bolt diameter and the endplate thickness the rotation capacity is increased. By modifying the bolt arrangement particular by increasing the distance of the bolts to the beam web and beam flange the rotation capacity is also increased. A test series in [9] examined the influence of the steel strength and the simultaneous activation of the components endplate and column flange in bending. The resulting moment-rotation curves are given in Figure 5a. By reducing the steel grade of the endplate and the column flange the rotation capacity is also increased accompanied by only small decrease of the resistance as, see e.g. test curves Z6 and Z3 in Figure 5a.

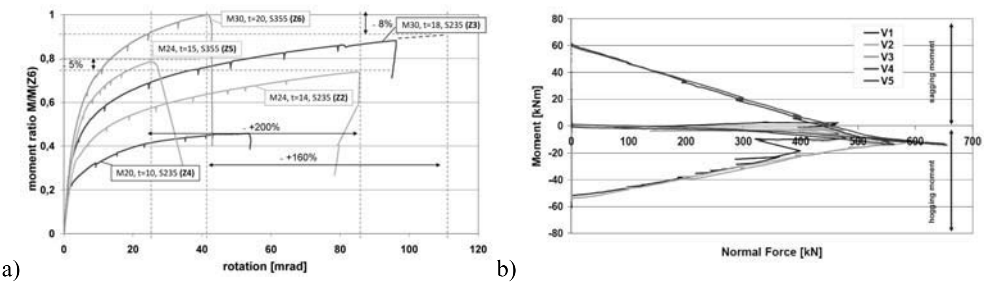


Figure 5: a) Influence of the steel grade to the rotation capacity and b) measured M-N-interaction of the composite joint tests

The objective of the composite joint tests was the determination of the simultaneous moment-tensile-resistance within the joint. The tests simulated the loading procedure from pure bending state to a mixed bending and tensile state up to a pure tensile state at the end. The tests were successfully following the whole theoretical M-N-curve (as shown in Figure 5b). The failure of the joints always occurred under mainly pure tensile exposure. From the results of the composite joint tests under combined bending and tension exposure it can be concluded that having a highly ductile joint behavior due to well-advised adjustment of the single components the transition from pure bending state up to a membrane state in the joint is feasible. The design of the joint specimens considered already over-strength effects and the bolts were intentionally oversized to exclude premature brittle failure of the connection. The results of the joints tests have been also con-firmed by a substructure tests executed by the project partner ULg (Liége, Belgium). Within this substructure test the activation of catenary action, after the event column loss happened, was possible due to the highly ductile performance of the joints [8]. Failure was mainly induced by the concrete slab: for the hogging moment joints by increased cracks and final rupture of the reinforcement, for the sagging moment joints by crushing of the concrete. In addition a remarkable residual resistance and ductility remained when the concrete slab had already failed.

5.3 Numerical investigations

The numerical simulations were executed by the Finite Element software ANSYS [1]. First recalculations were made to verify the FE-Model at the tests results and afterwards parametrical studies followed to extend the range of parameters as well as investigate the actual influence of material over-strength effects on the joint behavior. The influence of the material properties on the joint behavior (ductility and bearing capacity) depending on stochastic distribution of the material strength was investigated in a first step by considering various combinations of characteristic, see Figure 6a-c [9]. Numerical simulations were used due to the fact that the local membrane effect in the T-stub of the components “endplate in bending” or “column flange in bending” is not yet implemented in the analytical approach of the component method acc. to EN 1993-1-8 [1][4].

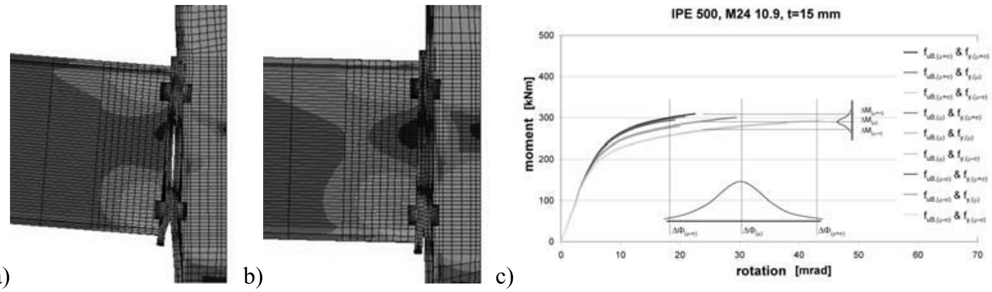


Figure 6: Deformed shape of steel joint considering a) nominal material values and b) over-strength effects and c) Moment–rotation curves for varied material strengths

In terms of resistance the over-strength effects usually cause an additional material reserve which can be activated in the case of progressive collapse analyses. But considering connections where different types of steel grade are assembled the over-strength effects may result in unintentional negative effects. Particular limited ductility is the main phenomena as the distribution of the available joint rotation depending on the statistical spread of the material properties in the diagram of Figure 6 shows.

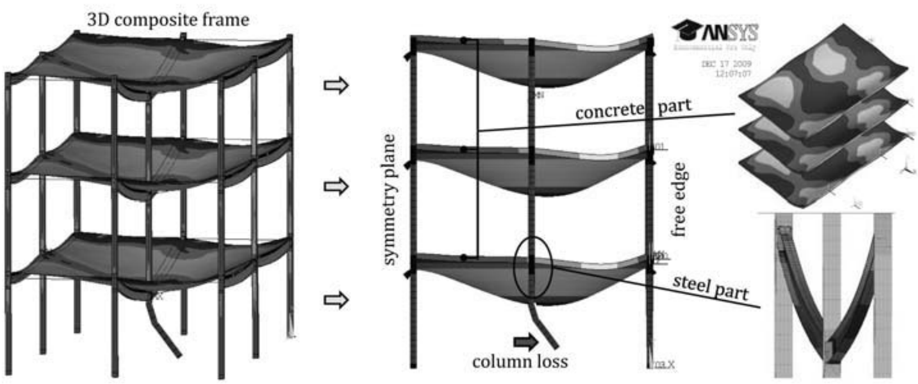


Figure 7: Simulation of column loss in a composite frame

Within a current diploma thesis numerical simulations on global level at steel and composite structures have been performed to analyze the collapse resistance of the structure as well as requirements for the implemented partial-strength joint configurations. Another aspect is also to determine the additional positive contribution of the continuous RC slab in two horizontal directions, see Figure 7. [7]

First results showed that such a composite beam-column structure is able to resist the event of a column loss under the accidental load combination for about 70-80% utilization of ULS loading. The identified requirements for the partial-strength joints concerning ductility and M-N-resistance are also feasible and within the range of the available rotation capacity and strength determined by the experimental investigation.

6 CONCLUSIONS AND ACKNOWLEDGMENT

As terrorist attacks become more and more frequent the demand of building safety has been raised. Under such exceptional loading situations, the ability of a structure to survive largely depends on the performance of key structural elements and their connections, preventing progressive collapse. But until now, aside of some theoretical concepts there are only very few and/or insufficient recommendations in the codes. Whereas heavy reinforced concrete buildings are generally regarded as safe, light steel framed structures have to provide evidence of a sufficient robustness against impact or blast in order to be accepted.

However, former and ongoing research projects have shown that intelligent robust design concepts such as the alternate load path method achieved by ductile joints solutions lead to advantages of steel and composite structures. In comparison to RC structures, steel and composite structures combine the characteristics high strength, ductility, great plastic reserves, high residual strength and energy dissipation. Furthermore the own research activity showed that obviously intelligent and highly ductile joint design is increasing the robustness of the structure. So by only small additional effort in joint de-sign additional resistance for exceptional loadings such as column loss may be activated.

Part of the work presented here is carried out, as a joint research project by different European partners, with a financial grant from the Research Fund for Coal and Steel (RFCS) of the European Community. The authors like to thank their partners for co-operation and gratefully acknowledge the financial support, also from the German funding of AiF.

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