Robust composite joints

G Skarmoutsos, N Keller and U Kuhlmann
Institute of Structural Design, University of Stuttgart, Pfaffenwaldring 7, Stuttgart 70569, Germany
sekretariat@ke.uni-stuttgart.de

Abstract. “Disasters” such as seismic events, impact or fire loading to structural elements of crucial importance highlight the significance of structural design for robustness. Consequently, exceptional load scenarios are to be considered. The question whether the joints of structures designed according to the current version of Eurocodes have adequate load bearing and deformation capacity for such load cases arises. The “alternate load path method” plays a key role in structural design for robustness. By using this design approach, redistribution and distribution of the existing and additional loads, respectively, to the intact structural elements should be enabled after a local failure such as “loss of a column”, preventing so the progressive collapse of the structure. In order to pursue the aforementioned goal, sufficient bearing as well as rotational capacity of the joints are required. In particular, for exceptional events, change of the moment’s sign in the area of the joints is often to be observed. However, until today, attention has been paid mainly to the response of composite joints under negative moments. Herein, besides this load case, the corresponding one of positive moments is investigated as well as the development of a membrane action that supports the load redistribution but requires a tension force capacity of the joints. Experimental research for the load case “loss of a column” was undertaken on both single composite joint specimens and composite frames. Also, an integrated design method, the beamline method, is analysed and constructional recommendations for design of ductile composite joints were developed and are herein presented.

1. Introduction

1.1. General
Robustness aims to mitigate a progressive collapse of the entire structure due to a local damage and prevent any disproportionate to the original cause extend of damage to the structure, setting as first priority in such way and above all, the human life. At the same time, increased robustness of structures achieved through simple measures such as ductile joints lead to more reliable structures, since the risk of collapse or severe damage to the construction is significantly reduced, without high amount of costs.

1.2. Design strategy “Alternate load path method”
One possibility to fulfil the robustness requirements, given in the current Eurocode for accidental actions [1] is to accept the local damage, complete loss of column, and to activate alternate load paths aiming to redistribute the existing and distribute the additional loadings into the intact parts of the structure. In order to achieve the above mentioned goal, the composite joints should have sufficient load bearing capacity (both for undamaged & damaged system) as well as rotational capacity for the load case that
arises after the investigated damage scenario has taken place (damaged system). Robustness of the structure is achieved through robust composite joints, being both ductile and able to activate the catenary action.

In more detail, ductile joints with high rotational capacity enable, once the column is lost, the following two mechanisms, which contribute towards the prevention of global collapse:

- The additional moments resulting from the column loss will be received from both the affected external and internal joints and the composite beam (see figure 1), the structural system of which has changed. As a consequence of this system change, the negative bending moments at the external joints increase, while at the internal joints positive bending moments are initiated. The fact that the composite joints are able to preserve or even increase their load bearing capacity while at the same time deform (rotate) makes them able to dissipate energy, induced by the impact loading, and also allows for the plastification of the composite beam in the area of span and supports. As a result, the additional plastic reserves of the system are activated as an alternate load path.

- In case the mechanism stated above is not able to prevent the global collapse of the structure due to severe additional loadings, one supplementary mechanism, this of catenary action, can develop. The membrane effect, or catenary action, may only be evoked, if an intact rest of the structure fixes the deformed beam horizontally. Only then, the axial stiffness of the composite beam can be activated and consequently axial forces developed. Once the column is lost, deflection of the composite beam’s axis is observed, while the two adjacent joints are further loaded with additional moments. These additional moments cause additional rotation of the two joints. As the rotation of the joints increases the deflection of the composite beam increases, too. For a certain value of joints’ rotation and consequently beam’s deflection from its original axis, the beam’s axial stiffness is activated and the composite beam carries a significant amount of axial force, contributing in such way effectively to the distribution of the additional loadings to intact parts. At that point, the moment at the joints is reduced, while the same could not be stated for the joints’ rotation and the reason why, is the already plasticised joints’ components.

It should be noticed that the joints are not only exposed to a hogging (negative) moment loading (joint adjacent to lost column), but due to the column loss also to sagging (positive) moment loading (joint directly above column loss), see figure 1.

![Figure 1. Catenary action in a 2D frame system through redistribution of M- into N-loading.](image)

2. Experimental investigations

2.1. General

Within two finalised research projects [2, 3] experimental investigations have been performed as part of a complete test campaign [3] in order to evaluate the behaviour of steel concrete composite joints concerning their possibility to fulfil the requirements resulting from the loss of an internal column. In these
projects, the research was focused on the composite joints’ load bearing and rotational capacity during single joints tests as well as full frame tests, for the load case “loss of a column”.

2.2. Tests on composite joints

2.2.1. Test program & test setup. Within eight experiments, the behaviour of composite beam-to-column joints under combined M-N loading was examined. As already mentioned, not only hogging moment loading is observed at the joints’ area during a column loss but also sagging moment loading (see figure 1). Therefore, four test specimens were exposed to hogging bending moment and four test specimens to sagging bending moment. For each of the two groups (hogging and sagging moment), the first specimen was first loaded with exclusively bending moment and in the following with axial force, too. The other three specimens were loaded throughout the whole duration of the experiment simultaneously with bending moment and axial force. Furthermore, the influence of a high loading speed, as it appears during a sudden column loss resulting for example from an impact, was investigated.

The tested composite joint configuration tested is shown in figure 2. It can be seen that the first shear stud is moved away from the column flange compared to a common joint configuration. Due to this increased distance, a ductile tension zone is available. The test setup for the joint tests under sagging moment loading can be found in figure 3. The width span between the hinged support and the middle column assumed as lost is 3.0 m.

In order to apply hogging moments, the test specimens were turned upside down. For this reason, the use of the same test setup for all joint tests was possible. With the help of the two horizontal jacks the axial force was applied to the joints.

![Figure 2. Joint configuration for joint tests [2].](image)
2.2.2. Test results & findings. The results in [2] showed that ductile failure of endplate in bending followed by bolt failure (failure mode 2 according to [4]) could be achieved for all joint tests, including those with high loading speed.

To be more specific, as it is depicted in figure 5 and figure 6 the specimens, which were first loaded only with bending moment load and in following additionally with axial force, were proven to have high rotational capacity (>30 mrad) already in the first part of the experiment. In the second part of it, the pure moment loading successfully converted, nearly fully, into axial force and the rotational capacity further increased. The aforementioned observations apply to both under hogging and sagging moment specimens (JT 1.1 & JT2.1).

Regarding the specimens which were simultaneously loaded with M-N loads (both under hogging and sagging moments), similar response was observed. The joints’ rotational capacity is high (>35 mrad), while the conversion of the moment loading into pure axial force was in that case slightly lower. For high loading speeds (70mm/sec & 140 mm/sec), the specimens under sagging moments, loaded simultaneously with M-N failed at 30% higher value of N in comparison to the respective specimens, for which a loading speed equal to 0,02mm/sec was applied. The explanation for this difference is to be found in the strain rate effect. Similarly, for the joint specimens under hogging moments the corresponding difference of N, at failure stage, for the use of high and low loading speed was 10%.

The fact that for sagging moments the strain rate effect affected at a greater extent the value of the axial force at which failure occurred leads to the following conclusion: the influence of the loading speed on the behaviour of the joints is dependent on the failing component.

![Figure 3](image3.png)  
**Figure 3.** Test setup of composite joint tests. [2]  

![Figure 4](image4.png)  
**Figure 4.** Qualitative stress distribution in proximity of the joint. [2]  

![Figure 5](image5.png)  
**Figure 5.** M-N-curves of the composite joints [2].  

![Figure 6](image6.png)  
**Figure 6.** M-Φ-curves of the composite joints [2].
It should be noted that the composite beams in the area of the joint, where no shear studs are applied, do not any more show a mechanical composite behavior, but they carry loads as two mechanically independent parts, reinforced concrete slab and steel beam. Therefore, both parts are exposed to tension as well as to compression loading (figure 4).

Based on all the above comments of subsection 2.2., it turns out that: the investigated composite joints being ductile allow for a redistribution of the moments along the affected composite beam taking advantage of the plastic reserves of the structural system and at the same time are capable to be part of an appropriate structural system, which may enable the development of the membrane effect.

2.3. Tests on composite frames

2.3.1. Test program & test setup. Additionally to the joint tests, two experimental tests on 2D composite frames were performed. Within these tests, the response of the adjacent to the lost column joint and of the two external joints was investigated (see figure 1).

The joint configuration of the first frame test was identical to the configuration of the joint tests (see figure 2). For the second frame test, the steel part of the joint configuration was modified (see figure 7). Specifically, the bolt diameter was increased from M20 to M24 and meanwhile, the horizontal distance from the endplate’s bolt holes to the beam web was increased, aiming in such way to achieve larger deformations and therefore to reach a higher ductility of the endplate as defined in [5].

The test specimen and the test setup of the composite frame tests are shown in figure 8. The span width between the external and the internal (lost) column was 5.0 m. Bags filled with sand (see figure 8) were placed on the reinforced concrete slab, simulating so the uniformly distributed load. After applying the bags, the lower vertical jack, playing the role of the middle column, was discharged so that the investigated load case was reproduced. Afterwards, the upper vertical jack was activated applying a vertical force (carried as moment loading by the joints), which in reality is expected to originate from the upper storeys (intact column above the internal joint).

2.3.2. Test results & findings. In the first frame test, a preliminary failure of the bolts at the middle column took place. The specimens of the second frame test were modified with larger endplates (distance from beam’s steel profile web to the bolt was increased) and higher diameter bolts. The second frame test proved to have increased ductility (i) locally, at the steel end-plate connection, and (ii) globally, with the composite beam reaching a vertical displacement of more than 600 mm (see Figure 8 & 9).
Figure 8. (a) Deformed test specimen of second frame test (b) External joint (c) Internal joint [2].

It could be observed that a failure of rebars under tension occurred at the external joints. However, the steel part of the joint was able to carry the loads despite of endplates’ large deformations (see figure 8). At the internal joint (see figure 8c) crushing of the concrete under compression occurred. The test was stopped when cracks at the welds evolved. Within the load-displacement curve of the second frame test in figure 9, the effect of catenary action is clearly recognized.

Due to the small amendments on the joint configuration, it was possible to reach a vertical displacement sufficiently high so that the moment loading transformed into axial force through development of the membrane effect. By starting the horizontal jacks, an increase of the applied vertical load was possible.

Figure 9. Vertical load-displacement curve of second frame test. [2]

2.4. Summary
The joint and frame tests’ results highlight the importance of composite joints’ high available rotation capacity, when catenary action is to be developed as an alternate load path method. In addition, effective constructional measures for improvement of the frame’s response to the examined load case were implemented and proposed.
3. Verification of the rotation capacity of joints

3.1. General
Nowadays only deemed-to-satisfy rules are available in [4], no possibility for explicit calculation and verification of joints’ rotation capacity as part of the global system is given. Moreover, these rules refer only to permanent design situations, while exceptional load cases, as the one investigated herein, are not covered.

3.2. Beamline method
The above mentioned verification could be conducted with the help of the so-called beamline method. Within [2] and [6] the application of this method in sway and non-sway frames under permanent load cases was investigated.

The beamline method consists of a simple M-Φ diagram, where 2 types of lines are to be plotted:

1. A line (e.g. green and blue line in figure 11) representing the demanded load bearing and rotational capacity of a joint for the given structural system and load case.
2. The available M-Φ characteristic of a certain joint (red line).

Beamline method is an integrative design approach regarding the design of the structural system and choice of the joints as part of it, since in a single diagram both the requirements of the global structural system and the respective capacity of a joint as a local system are presented. If the two types of lines intersect, then the investigated joint is capable of fulfilling the requirements of the examined structural system, for the given load case. If not, then local failure, of the joint, and consequently afterwards global failure is to be expected.

3.3. Examples
For an intact, non-sway frame system, the linear beamline varies simply between the rigid joint with available moment capacity but rotation capacity zero and the hinged joint with high rotation but zero load bearing capacity (see figure 10, points a and b respectively).

As it was shown in recently completed research projects [2, 3, 7] the beamline method could be used for structures under exceptional load cases, such as loss of a column, too.

In figure 11, the system characteristic for a non-sway reference structure under the load case “loss of an internal column” is illustrated. The global system’s M-Φ characteristic lines (green and blue lines) and the joint’s available M-Φ characteristic line (red line) are both plotted for the directly affected joint (sagging moment) as well as for the indirectly affected joint (hogging moment). It can be observed that load bearing and rotational capacity of the joint tests calculated according to [8], and presented in figure 11, are not sufficient as no intersection point between the two curve types exists. However, the constructional improvements, regarding the joint setup, within frame test 2 proved advantageous regarding the load bearing and rotational capacity as well as ductility of the joints.
For all the above stated reasons beamline method is a simple, useful, descriptive tool able to verify load bearing and rotational capacity of joints and check if these fulfil the global system’s requirements, resulting from the relevant load case, column loss.

4. Outlook: Composite joints under cyclic loading

4.1. General
The investigated inversion of the moment’s sign, in the joints’ area, is observed at structures exposed to earthquake, too. In that case, the constructive measures for the structure represent the only way to fulfil the high requirements deriving from the earthquake, since the implementation of any precautionary design measures against the natural phenomenon is not possible. Of crucial importance for the composite structures’ response to the aforementioned load case are, again, the composite joints.

4.2. Component model
The composite joints are designed according to the component model as prescribed in [4] and [9] and thoroughly explained in [10], which calculates their stiffness and load bearing capacity accurately for static loads. However, when referring to earthquake, cyclic loading is expected. In that case, as presented in [11] & [12], the stiffness and the load bearing capacity of the joint could differ from the respective under static loads.

Moreover, joints may be used in seismic engineering, under certain limitations, as energy dissipating components of the structure (partial strength joints), distinguishing in such way even more their role in comparison to statically loaded joints. The ductility of the impact loaded joints described in the previous sections contributes towards the demanded energy dissipation in the area of the joints, but for seismic engineering additional requirements are to be fulfilled. These, aim to satisfy global stability criteria and to optimize the energy dissipation procedure, at local and global level, by using appropriate joint configurations able to produce full hysteretic curves and defining step by step the global plastic mechanism of the structure by means of nonlinear static or dynamic analyses, as defined in [13], respectively. The extension of the component model’s use to composite joints under cyclic loading, could provide analytical information about the response of each joint’s component and of the joint in total. This information would contribute to the prediction of the global system’s response, enabling the definition of the global plastic mechanism, since the nonlinear behaviour of the joints would be known. In such way the realization of capacity and performance based design for structures in seismic areas will be more effective and easy to achieve and a step forward regarding the realisation of resilient structures would have been done, since the designers will be able to plan for a more favourable, and under certain circumstances resilient, failure mode of the structure.
Acknowledgements
Gratefully acknowledged are the Research Fund for Coal and Steel (RFCS) of the European Community and AiF (“Otto von Guericke” e.V.) for the financial support as well as all partners for their good cooperation.

References
[1] CEN 2010 EN 1991-1-7: Eurocode 1: Actions on structures – Part 1-7: General Actions – Accidental Actions (Brussels: European Committee for Standardization)
[2] Kuhlmann U et al. 2016 Robust Impact Design of Steel and Composite Buildings: Final Report of the project RFSR-CT-2012-00029 (Brussels: European Commission)
[3] Hoffmann N and Kuhlmann U 2015 Außergewöhnliche Bemessungssituationen nach DIN EN 1991-1-7 Effektive Anwendung und Bemessungsstrategien für Stahl und Verbundrahmenwerke DAST/AiF research project No 17153
[4] CEN 2005 EN 1993-1-8: Eurocode 3: Design of steel structures – Part 1-8: Design of joints (Brussels: European Committee for Standardization)
[5] Rölle L 2013 Das Trag- und Verformungsverhalten geschraubter Stahl- und Verbundknoten bei vollplastischer Bemessung und in außergewöhnlichen Bemessungssituationen Doctoral Thesis (Stuttgart: University of Stuttgart - Institute of Structural Design)
[6] Schäfer M 2005 Zum Rotationsnachweis teiltragfähiger Verbundknoten in verschieblichen Verbundrahmen Doctoral Thesis (Stuttgart: University of Stuttgart - Institute of Structural Design)
[7] Hoffmann N Kuhlmann U et al. 2015 Robust Impact Design of Steel and Composite Buildings (Helsinki: Proc. of IABSE Workshop) p 38–53
[8] Hoffmann N (in prep.) Robustheit von Stahl- und Verbundrahmen durch gezielte Anschlussausbildung Doctoral Thesis (Stuttgart: University of Stuttgart - Institute of Structural Design)
[9] CEN 2010 EN 1994-1-1: Eurocode 4: Design of composite steel and concrete structures (Brussels: European Committee for Standardization)
[10] Kuhlmann U, Rölle L and Hoffmann N 2018 Verbundanschlüsse nach Eurocode Stahlbau 87(9) 809–79
[11] Kuhlmann U et al. 2015 High Strength Steel in Seismic Resistant Building Frames HSS-SERF Final Report of the Project RFSR-CT-2009-00024 (Brussels: European Commission)
[12] Landolfo R et al. 2017 European pre-QUALified steel JOINTS (EQUALJOINTS): Final Report of the project RFSR-CT-2013-00021 (Brussels: European Commission)
[13] CEN 2010 EN 1998 Eurocode 8: Design of structures for earthquake resistance (Brussels: European Committee for Standardization)