ANALYSES OF THE ROTATIONAL CAPACITY OF COMPOSITE CONNECTIONS FOR PLASTIC DESIGN

Oliver Hechler
ArcelorMittal Chair of Steel and Façade Engineering
University of Luxembourg
Luxembourg
Oliver.Hechler@uni.lu

Christoph Odenbreit
ArcelorMittal Chair of Steel and Façade Engineering
University of Luxembourg
Luxembourg
Christoph.Odenbreit@uni.lu

Jean-Pierre Jaspart
ArGEnCo Department, MS²F Division, Liège University,
Liège, Belgium
Jean-Pierre.Jaspart@ulg.ac.be

ABSTRACT

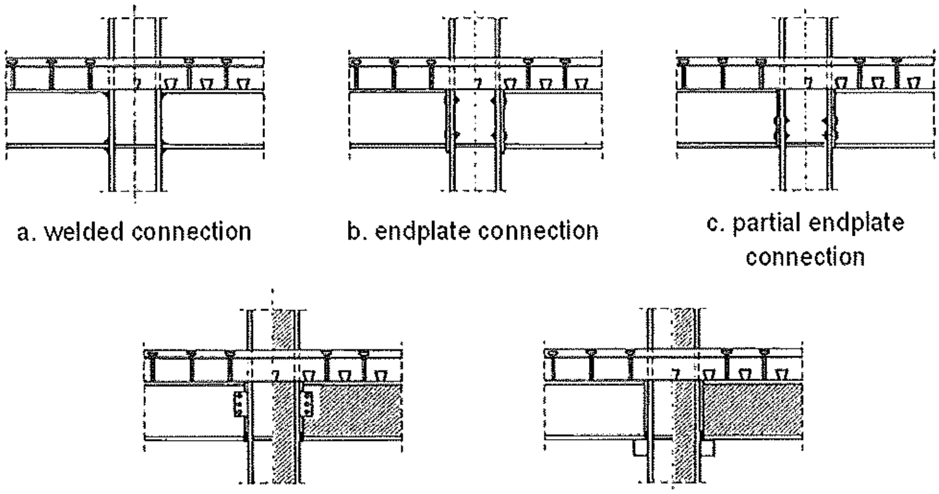
The demand for economic and eco-efficient solutions in construction industry is particularly enforcing efficient design and construction methods. The design of composite construction according to the plastic hinge theory in combination with semi-rigid joints provides one contemporary promising answer to these demands. This combination enables to mobilize almost all cross section- and system reserves. However, the capability for redistribution of the bending moment from internal support to mid-span, to activate these system reserves, requires sufficient rotation capacity of the composite beam and, especially, the connections. This paper presents design guidance on plastic and robust design of composite beams with semi-rigid composite connections with special focus on the influence of the reinforcement (ratio, diameter and type). With the provision of an engineering logic, new opportunities to design elegant and slender structures are given to engineers in a simple way.

INTRODUCTION

In composite construction, as for steel construction, the economic execution of the connection between the steel beam and the column is of decisive importance regarding the efficiency of the total slab system. Costly welding and precision work have to be avoided. Generally, composite connections can be designed either fully-rigid, semi-rigid or pinned. Figure 1 shows typical designs for moment resisting composite connections.

The fully rigid connection, providing full strength, has to have at least the same bending capacity as the connected beam. This means, that the steel-part of the connection has to offer not less than the bending resistance of the connected steel beam itself.

The pinned connection is the simplest solution. However, rotation and crack width control at the connection is challenging and the resistance of the section in negative bending is lost.



a. welded connection
b. endplate connection
c. partial endplate connection
d. finplate connection with compression plate
e. boltless connection

Fig. 1 – Types of composite connections [Odenbreit 1999]

The semi-rigid, partial strength composite connection is an efficient and economic intermediate solution between fully rigid and pinned connections with the following advantages:

a) Compared to the pinned connection:

- An optimization of the beam section is possible due to the activation of an additional bending resistance in the connection;
- The deflection in mid-span is reduced due to the restraint connection;
- The crack width in the connection zone in the serviceability limit state is controlled (reinforcement design).

b) Compared to the fully-rigid connection:

- Expensive construction details may be omitted (like for example stiffeners in the steel part of the connection) due to reduction of the negative bending moment because of redistribution of moment from connection to mid-span; the detailing and construction are simplified;
- Less reinforcement is required for connection design.

Particularly the combination of semi-rigid joints and design with the plastic hinge theory has a high potential to gain economic structures. Plastic hinges form generally at the supports where the composite connection is located. Therefore the bending resistance of the connection is reached before the bending resistance at mid-span is fully exploited. To activate this full moment capacity however, redistribution of the moments from the support into the field is necessary. This redistribution of moments increases the rotation in the connection.

Investigations [Odenbreit 1999] show, that beams with composite connections have the potential to reach their full plastic design capacity. However, the moment redistribution requires sufficient plastic rotation capacity in the connection. Thus, the relevant components of the connections have to be designed with enough ductile behavior. One decisive component on the rotational capacity is the ultimate strain capacity of the concrete chord in the negative bending moment area close to the column.

Designers generally lack information how to account for ductile behavior and how to design semi-rigid connections. Therefore this paper presents guidance on the design of semi-rigid composite connections with special focus on the influence of the reinforcement (type and ratio) on its rotational capacity.

DESIGN OF SEMI-RIGID COMPOSITE CONNECTIONS

The general design approach is to account for the stiffness of the connection for the calculation of the internal forces and subsequently check whether the design loads are lower than the resistance envelope as well as whether the rotation due to the loads $_{Ed}$ is not exceeding the ultimate rotation $_{u}$ of the connection. Therefore an engineering logic has been prepared and its steps are listed in the following.

(1) The bending stiffness of the composite section in uncracked (EI_1) and cracked (EI_2) conditions as well as the plastic moment resistance at mid-span $M_{F,pl,Rd}$ need to be calculated, see Figure 2.

(2) The bi-linear spring with the rotation stiffness S_j [Eq. (3)], plastic moment resistance $M_{j,Rd}$ on the basis of Eurocode 3 [EN 1993-1-8, 2005] with consideration of the reinforcement and the ultimate rotation capacity $_{u}$ [Eq. (4)] are to be determined.

It is to be remarked, that the non-linear rotational behavior of the connection, see Figure 6, is simplified and is considered as a bi-linear curve in step (2), see Figure 3.

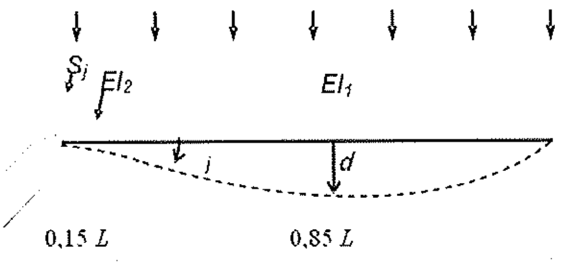


Fig. 2 – Consideration of the semi-rigid, partial strength connection in the structural system

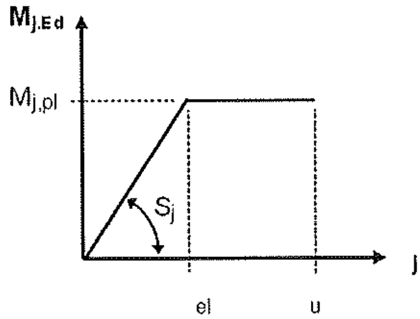


Fig. 3 – Bi-linear rotational curve of the connection for the static analysis

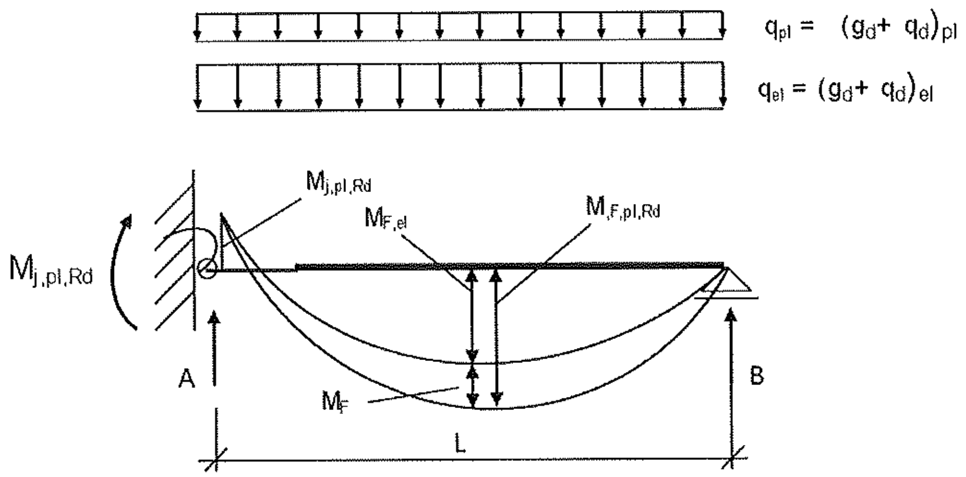


Fig. 4 – Illustration of the gain in design resistance from elastic analysis to plastic hinge theory for systems with semi-rigid connection

Semi-rigid, partial-strength connections should be accounted for in the structural analysis. Consistency is achieved by implementing a spring element in the structural system at the connection (see S_j in Figure 2) to account for the connections' stiffness. To consider the redistribution of moments, the calculation of the moment resistance capacity and related loading should be done according to step (3) and (4).

(3) The internal forces for the structural system, given in Figure 2, with EI_1, EI_2 and the spring stiffness S_j [Eq. (3)] are to be calculated with a linear-elastic analysis using the design limit of the connection resistance $M_{j,pl,Rd}$. From this analysis the related loading q_{el}, the moment in mid-span $M_{F,el}$ and the connection rotation $_{j,el}$ are to be estimated.

(4) In this step, the load will be increased from q_{el} to q_{pl} until $M_{F,pl,Rd}$ is reached to account for the redistribution of moment from support to mid-span after a plastic hinge has been formed at the connection, see Figure 4. Therefore the internal forces for the structural system given in Figure 2 with EI_1, EI_2 and by neglecting the connection stiffness (S_j = 0) are calculated according to the plastic hinge theory with a limit of the resistance in mid-span of $M_F = M_{F,pl,Rd} - M_{F,el}$; the related loading q_{pl} and the connection rotation $_{j,pl}$ is so obtained.

(5) Finally the following checks are to be performed to conclude the design:

$$q_{Rd} \quad q_{el} \quad q_{pl} \quad q_{Ed} \tag{1}$$

$$_{u} \quad _{j,el} \quad _{j,pl} \tag{2}$$

THE ROTATIONAL STIFFNESS

The rotational stiffness of the connection can be obtained through tests or by applying the component method given in Eurocode 3 [EN 1993-1-8, 2005]. In addition, investigations have been performed to obtain a relation between the stiffness S_j of the composite connection, see Figure 6, the stiffness EI_2 of the connected composite beam and the connection type. According to these ones, the following relation can be derived through the definition of a non-dimensional stiffness $s_{j,nd}$ [Odenbreit, 1999]:

$$S_j \quad \frac{s_{j,nd} \quad EI_2}{L_j} \tag{3}$$

with S_j = stiffness of the joint according to Figure 3 to be implemented as spring stiffness in the static system given in Figure 2, EI_2 = bending stiffness of the composite beam in negative bending, L_j = length of the composite connection, see Figure 5 [Odenbreit 1999] and $s_{j,nd}$ = non-dimensional stiffness parameter of the connection.

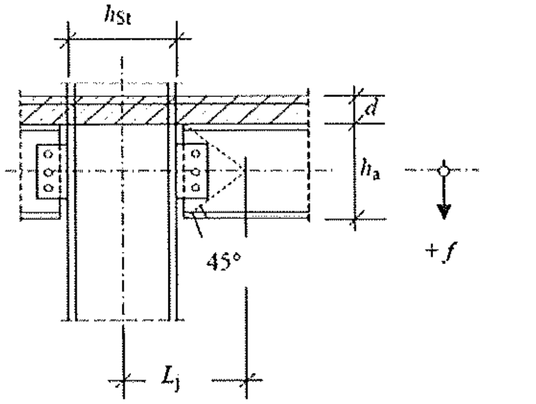


Fig. 5 –Definition of the length of the composite connection L_j [Odenbreit 1999]

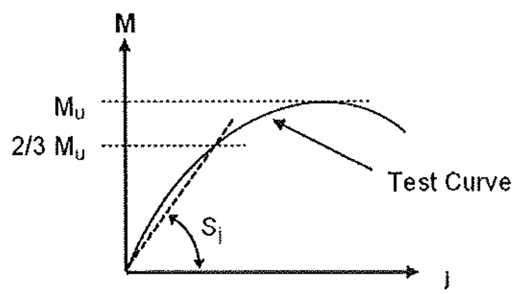
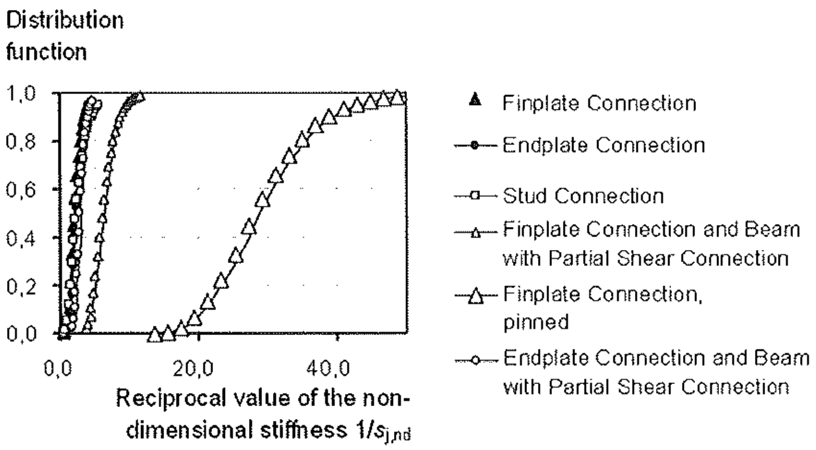


Fig. 6 –Definition of the spring stiffness S_j from experimental data [Odenbreit 1999]

The non-dimensional stiffness $s_{j,nd}$ has been empirically derived from statistical evaluation of 56 tests on different composite connections. It corresponds to the stiffness of the connection at 2/3 of the connections' ultimate moment capacity M_u, see Figure 6, and has been derived from the rotation-moment curves [Odenbreit 1999]. The distribution function of $s_{j,nd}$ is presented in Figure 7 and specific values for standard connections are listed.



- finplate connection: $1/s_{j,nd}$ 2,0,
- endplate connection: $1/s_{j,nd}$ 1.9,
- cleated connection: $1/s_{j,nd}$ 1.7,
- pinned connection: $1/s_{j,nd}$ 26.0.

Fig. 7 – Distribution function of the non-dimensional stiffness $s_{j,nd}$ and determined values for standard connections

THE PLASTIC BENDING RESISTANCE OF THE CONNECTION AND THE ULTIMATE ROTATION CAPACITY

The plastic bending resistance $M_{j,pl}$ is e.g. determined with the help of the component method given in Eurocode 3 [EN 1993-1-8, 2005] and additional consideration of the reinforcement bars in the concrete chord. In principle, the lower flange of the steel beam at the connection has to take over the compression forces and the reinforcement in the concrete slab the tension forces. In addition, the semi-rigid, partial-strength composite connection has, because of its reduced bending resistance, to assure the redistribution of a substantial part of the bending moment towards mid-span. The reduced plastic bending resistance in the connection has to be kept constant during plastic rotation (between $(M_{j,pl})$ and $_u$) in the plastic hinge, see Fig. 4.

The mentioned plastic rotation requires a considerable ductility in the connection. Brittle failure of any component must be avoided. To assure this ductility, structural specifications must be met, e.g.:

- The resistance of the steel plate must be lower than the shear resistance of the bolts,
- The bending resistance of the connection plate must be lower than the tension resistance of the bolts and
- The reinforcement in the concrete slab may not fail in a brittle way.

For the component "reinforced concrete in tension", the maximum rotation capacity $_u$, which can be provided, may be assessed with the following equation:

$$ {}_{u} \quad \frac{{}_{u}\, L_j}{h_j} \tag{4} $$

with L_j = length of the concrete component of the connection, h_j = height of the connection and $_u$ = ultimate strain of the reinforced concrete [Kreller 1990].

The ultimate strain in the reinforcement is to be derived by:

$$\varepsilon_u = \varepsilon_{s,y} - \beta_t \left(\varepsilon_{sr2} - \varepsilon_{sr1}\right) + \delta \left(1 - \beta \frac{\sigma_{sr1}}{f_{tk}}\right)\left(\varepsilon_{s2} - \varepsilon_{sy}\right) \tag{5}$$

with ε_{sy} = strain in the reinforcement at yield strength, $ß_t$ = 0.25 (for a permanent load and alternation of load), ε_{sr1} = strain in reinforcement at the first crack, σ_{sr1} = stress in reinforcement at the first crack ε_{sr2} = 0.0001, δ = factor to consider the different types of ductility of the reinforcement, f_{tk} = tension strength of the reinforcement and $ß$ = factor to distinguish between mesh and bar reinforcement. However, Equation (5) is yet not covering the influence of the bar diameter sufficiently.

THE INFLUENCE OF THE REINFORCEMENT DIAMETER ON THE ROTATION CAPACITY

The rotational capacity of the connection is significantly influenced by the reinforcement design of the composite connection. The determination of the strain and the elongation of the component "reinforced concrete in tension", see Equation 5, considers the degree and type of reinforcement; namely the factor ß distinguishes between mesh reinforcement (ß = 1.0) and bar reinforcement (ß = 0.85) [DIN 1045]. However tests showed [Odenbreit 1999], [Kindmann & Kathage 1994]), that this specification may not sufficient to account for the real behavior of the connection and its dependency on the bar diameter has to be considered.

Therefore a test campaign has been performed at the University of Luxembourg [Hahn 2009] to check the influence of the reinforcement component on the design of composite connection with plastic hinge theory. The test setup and specimens for the connection assembly have been construed in reference to [Kindmann & Kathage 1994], see Figure 9.

This configuration has been chosen so as the moment in the connection can be clearly divided into a compression and tension component. The compression component is directly transmitted horizontally into the lower flange of the connected beam; the tension component is exclusively taken over by the reinforcement in the concrete chord. The shear is directly transmitted via the end plate into a cleat and is therefore not interacting with the tension and compression components.

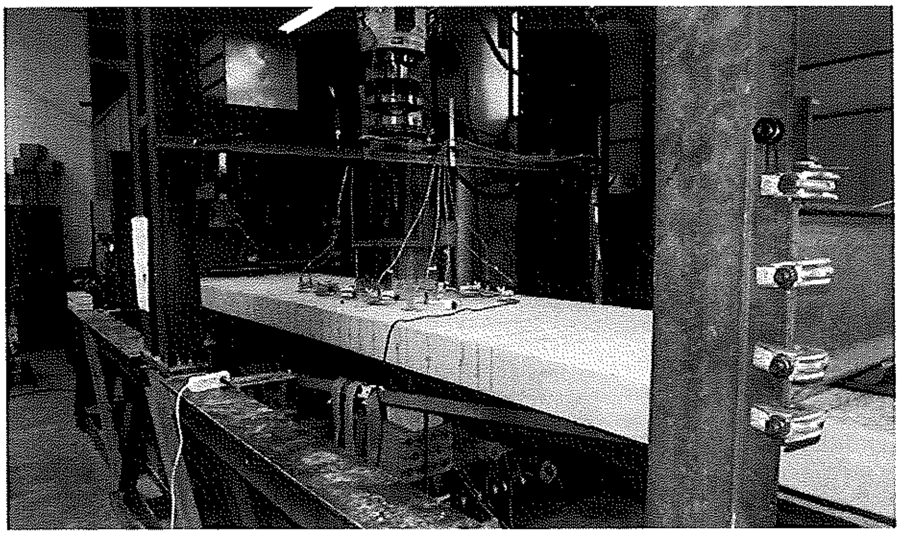


Fig. 8 – Test assembly in the laboratory for structural engineering of the University of Luxembourg [Hahn 2009]

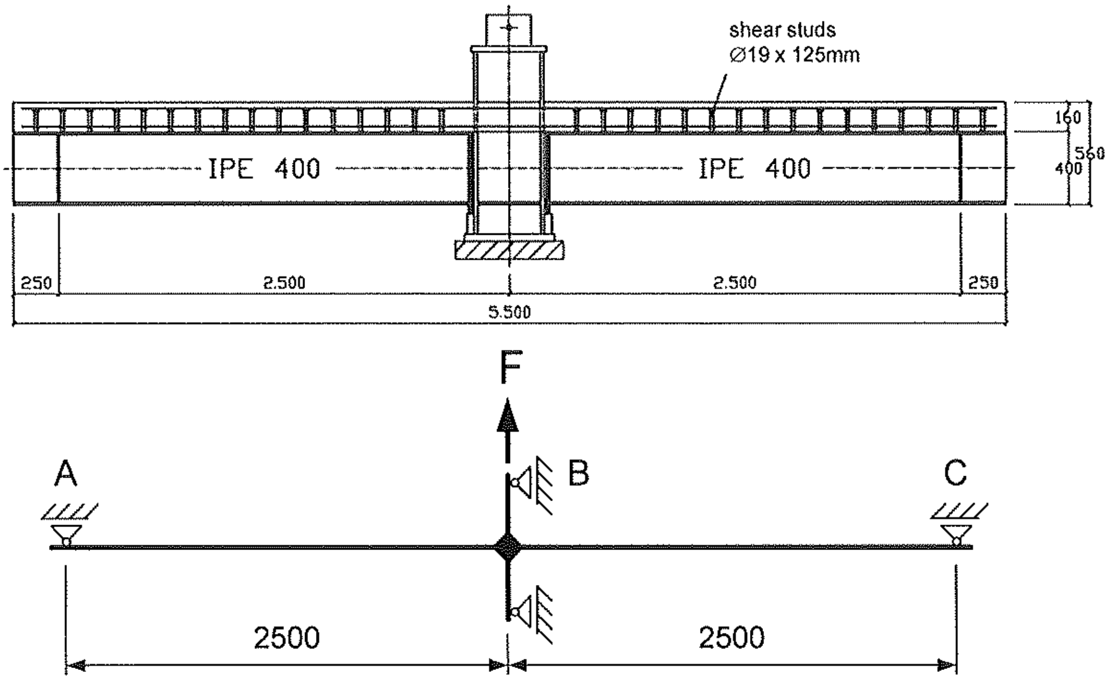


Fig. 9 – Test setup and static system [Hahn 2009]

For all tests, the constructional detailing of the connections has been kept identical but the diameter of the reinforcement bar has been varied. An overview on the test campaign is given in Table 1.

Table 1 – Overview of test programme

Test series specification	ρ_s [%]	Reinforcement (BSt 500) Ø = 8 mm	Ø = 10 mm	Ø = 12 mm	R513	R589	Q513 + Ø = 12 mm
[Hahn 2009]	0.63	A-2					
	0.63				A-1		
	0.71			A-3			
	1.04	A-5					
	1.11						A-4
[Kindmann & Kathage 1994]	0.74		VT 2.1			VT 2.2	
	1.06			VT 1.1			
	1.41			VT 2.4			

For the connection design the steel compression component has been over-dimensioned, to achieve a very stiff compression component which deformation is negligible for the estimation of the connections' rotation. The degree of shear connection between concrete chord and steel beam (studs Ø19 mm) has been designed to be 100%. The compression members have been checked against stability failure.

The static system of the test setup is shown in Figure 9. The supports A and C are pinned supports and linked to the testing rig; the hydraulic jack is located at the support B and is pulling deflection controlled with a force F.

For each test, a pre-loading with 10 cycles of the load range from 5% to 40% of the ultimate load expected has been applied to loosen any bonding and exclude settlement of the testing frame. Subsequently the test has been loaded in small deflection increments until failure. To measure deflections, slip in the shear joint and rotations, 26 displacement transducers (W) and three inclinometers (I) have been used, see Figure 10.

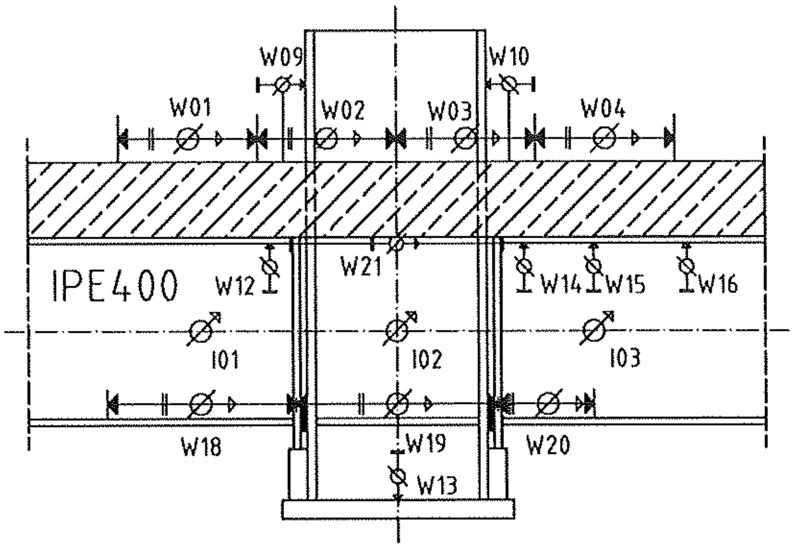


Fig. 10 – Measurement campaign for each test setup [Hahn 2009]

As planned, all test failed due to tension failure of the reinforcement bars. The crack pattern of the test specimens is similar; exemplary the crack pattern for test A-5 is shown in Figures 11 and 12. The crack, in which finally the failure took place, has appeared after the pre-loading already. It has been initiated at the outer edge of the columns' flange and has grown toward the edge of the concrete chord to the location of the first transversal reinforcement. In Table 2 the results of the test presented in this paper [Hahn 2009] as well as previous test [Kindmann & Kathage 1994] are listed.

Table 2 – Collection of test results

	Series	Reinforcement	ρ_s [%]	$M_{pl,cal}^{***}$ [kNm]	$M_{pl,cal}^{***}$ [kNm]	$M_{u,test}$ / $M_{pl,cal}$	Φ_{test} [mrad]	$S_{j,test}^{****}$ [kNm/rad]	Failure
[Hahn 2009]	A-1	R 513	0.64	320.6	275.4	0.86	9.0	87847	R*
	A-2	∅ = 8 mm	0.63	364.9	363.3	1.00	22.1	76639	R
	A-3	∅ = 12 mm	0.71	402.1	416.0	1.03	45.7	81817	R
	A-4	Q 513 + ∅ = 8 mm	1.11	595.4	557.9	0.94	14.9	78302	R
	A-5	∅ = 8 mm	1.04	582.5	582.5	1.00	43.8	88258	R
[Kindmann & Kathage 1994]	VT 1.1	∅ = 12 mm	1.06	538.0	595.0	1.11	67.7	88344	R/B**
	VT 2.1	∅ = 10 mm	0.74	382.0	425.0	1.11	36.0	88266	R
	VT 2.2	R 589	0.74	380.0	396.0	1.04	9.2	95652	R
	VT 2.4	∅ = 12 mm	1.41	659.0	770.0	1.17	70.6	322851	R/B

* Rupture of reinforcement
** Buckling of steel section
*** acc. to [8] with material properties from testing
**** acc. to [8]

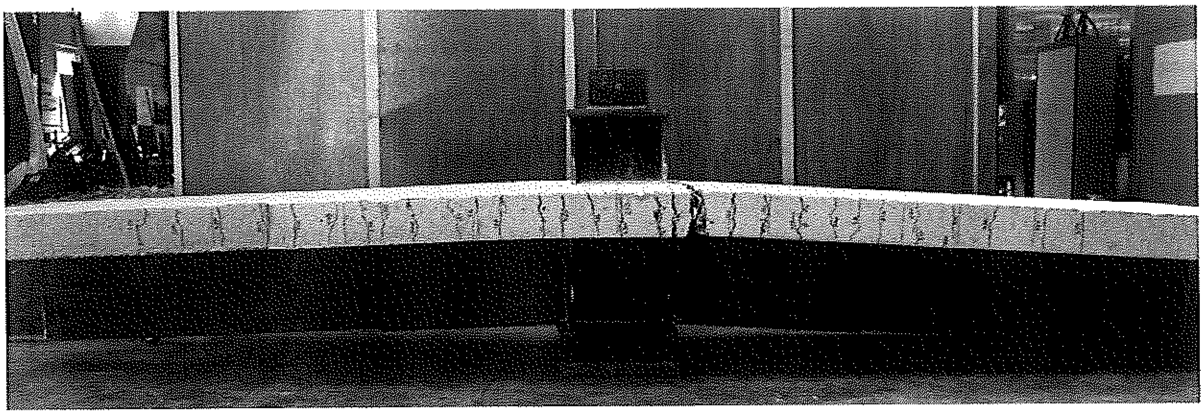


Fig. 11 – Side elevation of failed test specimen (Test A-5)

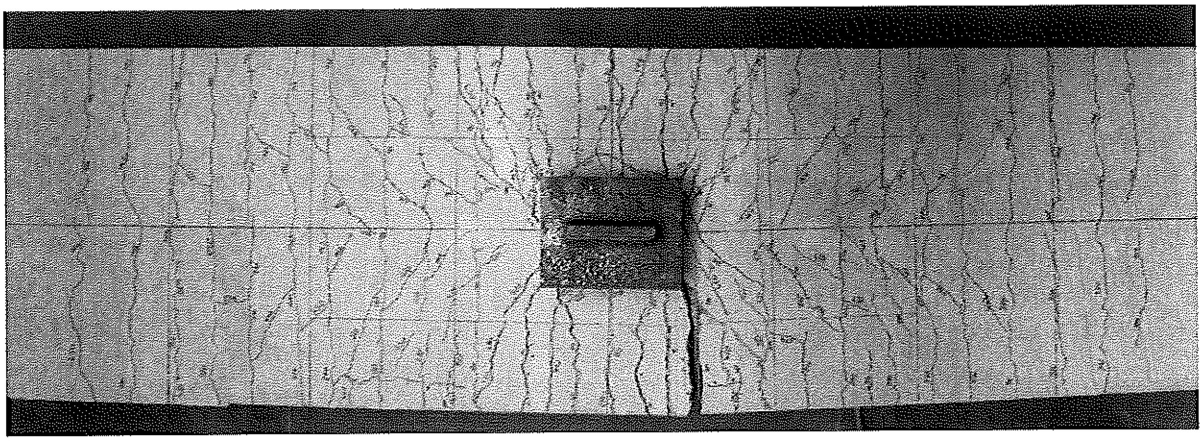


Fig. 12 – Top view on failed test specimen (Test A-5)

From the test it is to be concluded that:
(1) an increase of the degree of reinforcement, without changing the reinforcement diameter and the overall connection assembly, leads to an increase in stiffness of the connection (concluded from comparing tests A-2 with A-5 [∅8] as well as A-3 and VT 1.1 with VT 2.4 [∅12], see Figure 13);
(2) an increase of the degree of reinforcement, without changing the reinforcement diameter and the overall connection assembly, also the rotation capacity of the connection is increasing (concluded from the same comparison as above);
(3) with increase of the reinforcement bar diameter and constant degree of reinforcement the rotational capacity of the connection is increased (concluded from the comparison of tests A-2 with VT 2.1 and A-3, see Figure 14);
(4) the application of mesh reinforcement has a negative impact on the rotation capacity of the connection (concluded from the comparison of test A-1 with A-2 and VT 2.2 with A-3, see Figure 15); even additional bar reinforcement is not able to compensate this deficit significantly (comparison of A-4 with A-5, see Figure 15).

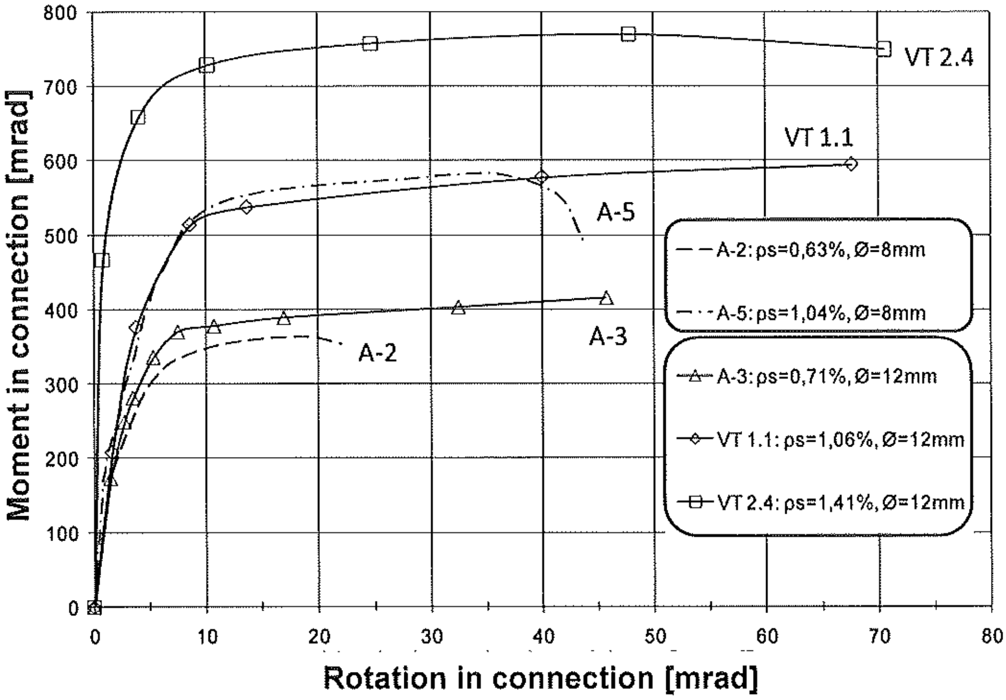


Fig. 13 – Comparison of the rotation-moment curves for tests with varying reinforcement ratio and constant reinforcement diameter

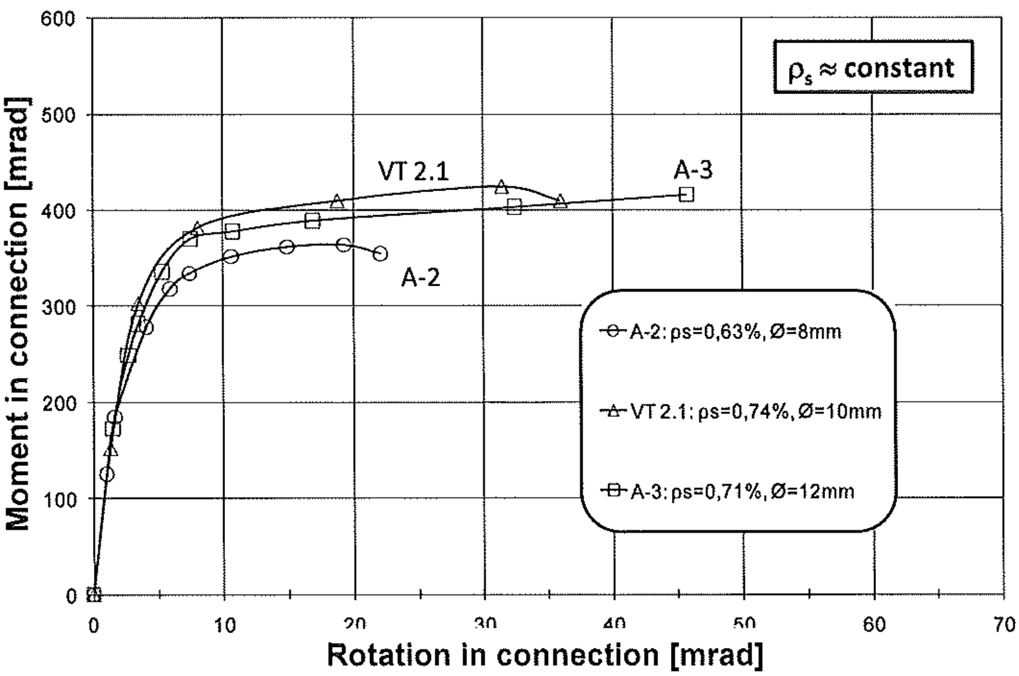


Fig. 14 – Comparison of the rotation-moment curves for tests with constant reinforcement ratio and varying reinforcement diameter

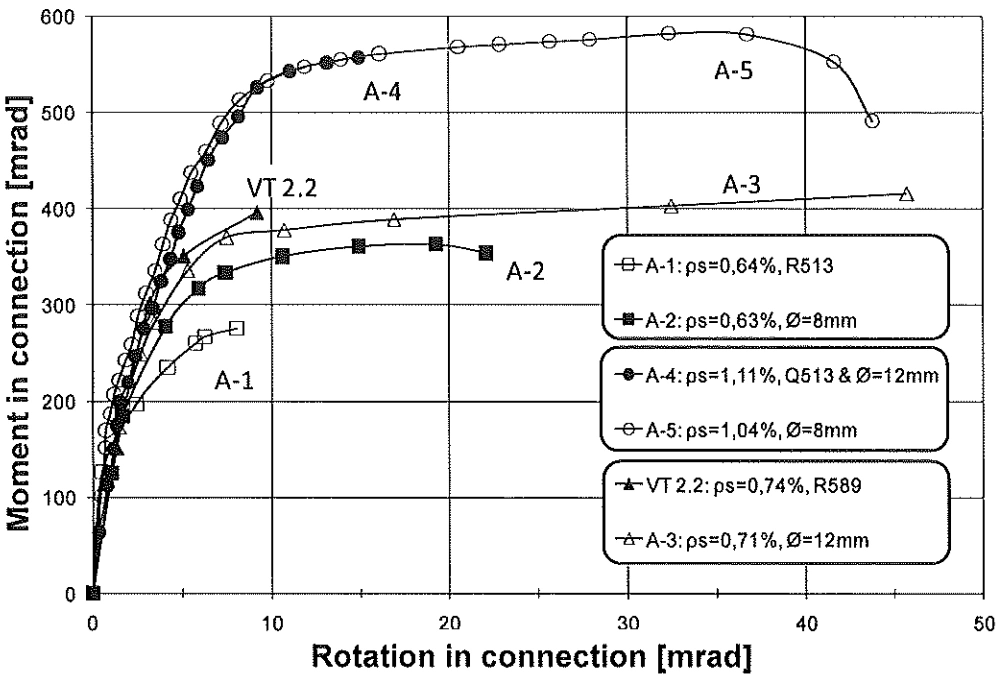


Fig. 15 – Comparison of the rotation-moment curves for tests with varying type of reinforcement (bar vs. mesh reinforcement)

As almost the whole rotation of the tested composite connections results from strains in the concrete chord, conclusion (1) is considered in Equation (3) (in the EI_2) and conclusion (2) is already accounted for in Equation (5) appropriately. However the increase in rotation capacity in dependency of the bar diameter as well as the decrease in reference to the type of reinforcement is not yet covered.

The increase in the rotation capacity due to the increase in bar diameter results from the following conditions:

(1) the extreme negative bending moment is located at the support, thus in the zone of the connection;

(2) the connection is rotating around the contact area of lower flange of the steel beam with the support and therefore pulls locally away the concrete chord from the column;

(3) due to the penetration of the column through the concrete chord, see Figures 11 and 12, the point of crack initiation for the concrete chord are predefined.

In the consequence the negative bending moment at the connection causes only very few major cracks at the beam end connection in the concrete. Larger reinforcement bars have a higher crack opening potential due to their bigger anchorage length; therefore the rotation capacity of the connection increases with increasing bar diameter. This positive effect needs to be reflected in terms of the review of the factor ß in Equation (5).

The negative effect of the application of meshes as longitudinal reinforcement is resulting from the restriction in anchorage length to the distance of the perpendicular welded reinforcement bars (mesh size) and therefore, the elongation length for the strains in the major cracks. In the consequence, the impact of the type of reinforcement is to be sustained in the review of the factor ß in Equation (5).

CONCLUSIONS

This paper presented a design logic for the design of composite construction according to the plastic hinge theory in combination with semi-rigid joints. Design equations for all relevant parameters are explained and values, when relevant, are provided. Special focus has been put on the experimental analyses of the rotation capacity of composite connections required for the robust design of these kinds of structures. Hereby the significant influence of the reinforcement (ratio, diameter and type) on the rotation capacity has been demonstrated. Research potential how to account for this influence has been outlined.

The presented design logic is based on the evaluation of 9 self-conducted tests and on the evaluation of 74 tests on composite connections from all over Europe. The analysis of these tests and accompanying non-linear numerical investigations proofed, that a simplified characterization of the non-linear behaviour of the connection by a bi-linear law is sufficiently exact to determine the displacements at serviceability limit state as well as the load-bearing capacity at ultimate limit state [Odenbreit 1999]. Therefore a robust method has been presented to design efficient and thus economic structures in a simple way.

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