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BEHAVIOUR OF STEEL-TO-CONCRETE JOINTS

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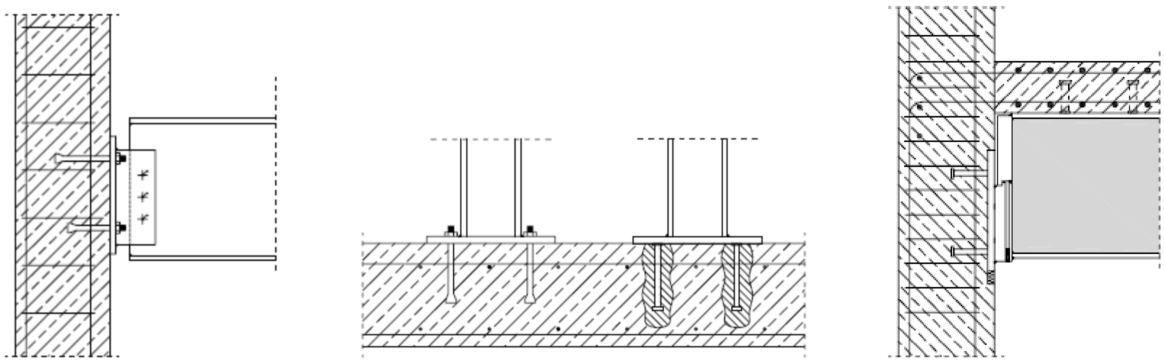
Abstract: This paper presents the innovative solutions to connect steel and composite beams to structural reinforced concrete walls developed within the RFCS research project "InFaSo". Two types of joints were studied: pinned and moment resistant. The evaluation of the joints behaviour was performed experimentally and complemented with the development of analytical component based models. The comparison of results showed a good agreement between models and experiments. The analyzed joints demonstrated to be competitive solutions taken into account their structural performance, simplicity of modelling and of execution.

1. Introduction

In mixed buildings various steel or composite elements like girders, columns or bracing ties have to be connected to concrete members like staircases and fire protection walls, columns or foundations. An effective solution to realize steel-to-concrete joints is the application of anchor plates with welded headed studs or other fasteners.
Aiming at the study of steel-to-concrete joints the RFCS project "New market chances for steel structures by innovative fastening solutions between steel and concrete" ("InFaSo" [1]) was launched. Three types of joint joints were subject of study: i) pinned beam-to-wall (Fig. 1-a); ii) column bases (Fig. 1-b); iii) moment resistant composite beam-to-wall (Fig. 1-c). In order to evaluate the joints properties an experimental programme was accomplished and analytical models developed within the project tasks. The proposed models are based on the component method which had already been introduced for steel and composite joints in EN 1993-1-8 [2] and EN 1994-1-1 [3]. The extension of the method to steel-to-concrete joints requires the characterization of "new" components activated in this type of joints. These involve essentially the participation of the concrete on the possible modes of failure of the joint.
In the present paper the developments of the InFaSo research project on the pinned and moment resistant joint are presented. The experimental results and the validation of the proposed analytical models are discussed.



a) Pinned b) Column base c) Moment resistant

Fig. 1: InFaSo studied joints [1]

2. Component method and additional components in steel-to-concrete joints

2.1 General description

The application of the component method offers the possibility to determine the structural joint behaviour like strength, stiffness and ductility. The concept is to identify each relevant joint component and to characterize its structural behaviour in terms of F-d response. By assembling the components the whole joint configuration can be modelled for joint analysis. The weakest component defined the joint behaviour.

In the current codes the component method is used for pure steel joints, and in a limited form for column bases and composite joints. The most components describing a concrete failure are not covered. Indeed the design of fastenings in concrete is ruled in the Technical Specification CEN/TS 250 [8], but there is no information about the stiffness and ductility included, and in terms of reinforced concrete it is quite conservative in many cases.

Therefore, the extension of the component method to steel-to-concrete joints was sought. In such joints, “new” components are activated which consider the concrete modes of failure associated to the anchorage in concrete using headed anchors. An overview of possible concrete components is given in Table 1, details may be found in [1]. Thus, experimental work on the “new” components and the proposal of analytical models was performed within “InFaSo” research project [1].

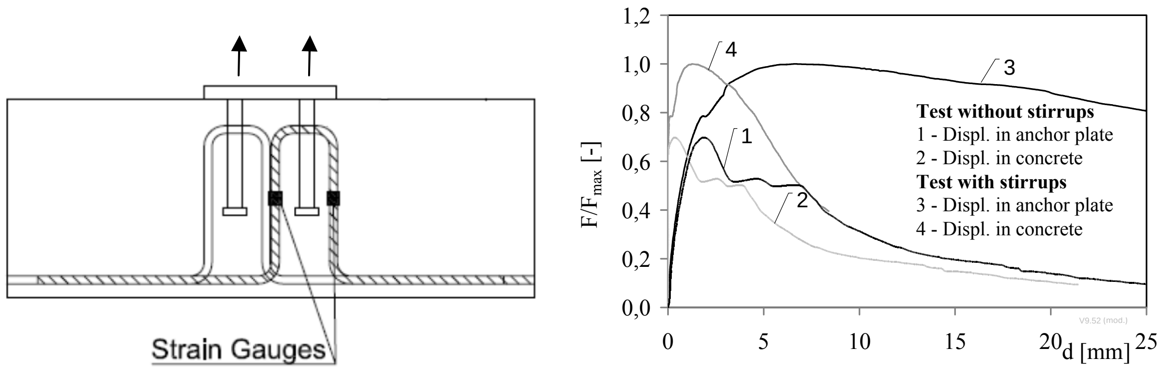
Table 1: List of new components activated in steel-to-concrete joints

Anchors in Tension		Anchors in Shear	
Failure mode	Component ID	Failure mode	Component ID
Concrete cone	T-CC	Concrete edge failure	V-CE
Pull-out/Pull-through failure	T-PO	Pry-out failure	V-PrO
Splitting failure	T-Sp	Pull-out failure	V-PO
Local blow-out failure	T-BO	Hanger reinforcement failure	V-HR
Hanger reinforcement failure	T-HR		

2.2 Investigations on concrete components

The investigations on concrete components within InFaSo [1], carried out by the team of Prof. Rolf Eligehausen and Prof. Jan Hofmann at the Institute of Construction Materials in Stuttgart (see [6]), were focussed on headed studs with stirrups in tension, in order to determine its strength and deformations as they are not included in the current codes. As shown in Fig. 2a a very simple and effective configuration of the stirrups was chosen for investigation, according to the project's aims. The component was included in the pinned steel-to-concrete joints tested within the project (see [1]).
Several groups of tests were performed, mainly on pure tension loading. The tests were carried out in non-cracked as well as cracked concrete, where the installed cracks crossed the anchor row, with and without stirrups. Also the position of the stirrups respectively the distance from the anchors was varied.

In Fig. 2b the relative load-displacements curves for two specimens, one without and one with hanger reinforcement, are given. The curves show the typical response of this type of anchorage. For each test, two curves are obtained, one representing the displacements measured in anchor plate and the other the displacements in the concrete. The latter allows identifying the contribution of the concrete cone component to the global deformation of the anchorage. In what concerns the use of hanger reinforcement, the results demonstrate that this type of reinforcement increases both the resistance and the deformation capacity of the anchorage. The use of strain gauges (Fig. 2a), allowed obtaining the force in the hanger reinforcement component and consequently quantify its contribution.



a) Test scheme [4]   b) Load-displacement response [5]

c)

Fig. 2: Experimental work on components

By the described measurement system during the component tests it was possible to identify the contribution of the concrete and stirrups separately as well as to define the descending branch of the concrete cone, and the loss of stiffness of this component respectively, due to the breaking of the concrete in tension. So the mechanical models proposed for different failure modes of headed studs with or without stirrups in tension allow not only a definition of the strength, but also the stiffness and ductility of the component and therefore are compliant with the component method in general. A detailed description of the proposed mechanical models for the concrete components tested within "InFaSo" can be found in [1] and [6].

3. Pinned joint of a steel beam to a reinforced concrete wall

3.1 General description

In the pinned joint configuration studied within the InFaSo project [1], the steel-to-concrete connection is accomplished using an anchor plate with welded headed studs. On the steel side, a steel cam or fin plate may be used to connect the steel beam through welding or bolting, respectively. The performed study was focused on the concrete side of the steel-to-concrete joint aiming the examination of the concrete components of the joint and their influence on each other. Thus experiments on joints were performed and a mechanical model, extending the field of application of the component method, was proposed.

3.2 Experimental research

The test programme was based on the joint solutions described above and illustrated in Fig. 1-a). Thus, a stiff anchor plate with two rows of headed anchors is connected to a reinforced concrete wall. The stiff anchor plate was used so that the concrete components were fully activated. The shear load was applied to the anchor plate with eccentricity. This eccentricity was varied according to the possible joint solutions. The joints were tested mainly in cracked concrete with and without hanger reinforcement. The cracks were installed perpendicular to the applied load and crossing the anchor row to be activated in tension due to the eccentricity of the shear load. Furthermore, the disposition and the length of the headed anchors were varied. In Table 2 the complete test programme is presented.

Table 2: Test programme for pinned steel-to-concrete joints [10]

Test specimen	Eccentricity [mm]	Anchorage length h_{ef} [mm]	Hanger reinforcement	Concrete condition	Disposition of anchors
B0-BS	53	160	-	non-cracked	2x3
B1-BS	53	160	-	cracked	2x3
B1-BS-R	53	160	Yes	cracked	2x3
B2-C	139	160	-	cracked	2x3
B2-C-R	139	160	Yes	cracked	2x3
R1-C	139	160	-	cracked	2x2
R1-C-R	139	160	Yes	cracked	2x2
R2-C	139	210	-	cracked	2x3
R2-C-R	139	210	Yes	cracked	2x3

In all tests failure was attained by concrete cone failure and/or pry-out failure. The simultaneously development of these two modes of failure are due to the loading conditions of the anchor plate, shear load and secondary bending moment. According to the level of the eccentricity, one of the failures modes becomes more relevant. In Fig. 3a comparison of the relative load-rotation behaviour of 4 test specimens is shown. Comparing the results of the specimens with hanger reinforcement (B1-BS-R and B2-C-R) with those without (B1-BS and B2-C) an increase of resistance and ductility of the joints is observed. In what respects to the effect of the eccentricity, in the test specimens with higher eccentricity, the maximum shear load was relatively smaller. In these cases, the tension concrete component governed the behaviour of the joint due to the higher tension introduced to anchor row on the tension side of the joint. For smaller eccentricities the joint behaviour was governed by the shear failure.

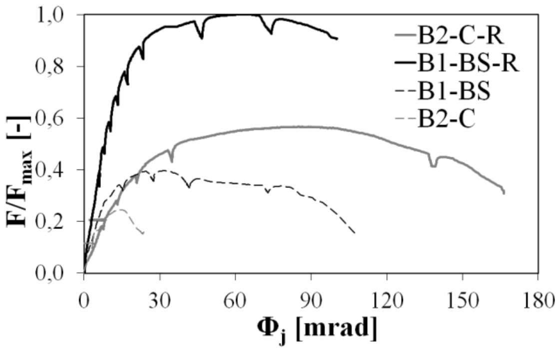
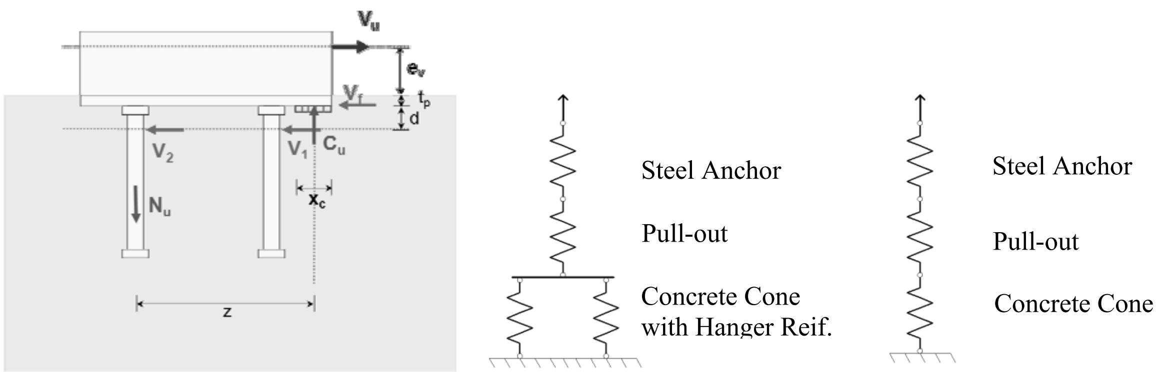


Fig. 3: Comparison between load-rotation curves of test specimens with and without stirrups [10]

3.3 Analytical approach

The focus of the experimental work was on the concrete components therefore, the developed mechanical model mainly consists of the components at the concrete side of the joint. The use of stiff anchor plate and steel cam/fin plate allowed neglecting their behaviour, as they didn't play a role.

In Fig. 4a the internal loading of the joint to equilibrate the external shear load V_u is illustrated. Due to the eccentricity of the latter, a secondary bending moment develops and consequently the tension components are activated on the non-loaded side of the plate (left side according to Fig. 4a. In Fig. 4b are represented the tension components to be considered in the model of the joint. Each component represents the possible failure modes associated to the anchorage in concrete. The contribution of hanger reinforcement is considered adding a spring parallel to the concrete cone component. A detailed description of these components may be found in [1].



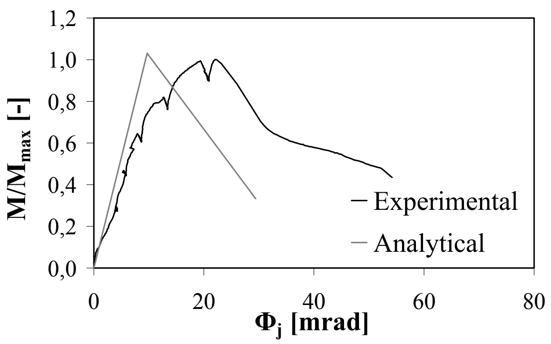
a) Representation of the joint loading

b) Model for the tension components

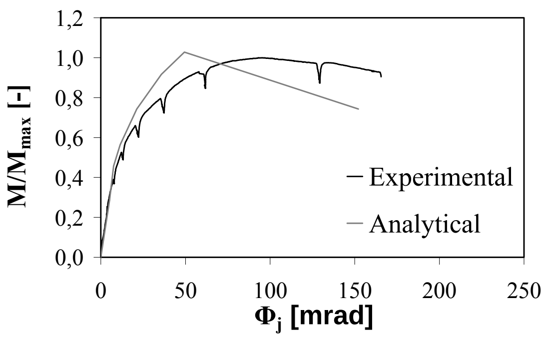
Fig. 4: Pinned joint model

For the compression zone, a rectangular stress block is assumed under the plate (see Fig. 4a). Here, the stresses are limited to $3f_{cm}$, as proposed in the CEN/TS 1992-4 [8]. The stress area A_c is given by the width of the anchor plate x_c (perpendicular to the load) and the length of the compression zone, which results from the equilibrium with the assumed tension force in the headed anchors on the non-loaded side. Thus, the internal lever arm z and the inner bending moment are calculated. The latter defines the resistance to the secondary bending moment introduced by the shear load applied with eccentricity. In what regards to the shear resistance, the contribution of the shear resistance of the anchors and the friction between the concrete surface and the anchor plate is considered. The friction resistance is proportional to the compression force defined above. In the model a friction coefficient μ=0,4 was used as proposed in [11]. The shear resistance of the anchorage is dependent of two possible failure modes: steel failure of the anchors shaft or pry-out failure of the concrete. Finally the anchor row on the non-loaded side is subjected simultaneously to tension and shear, therefore the interaction has to be taken into account. This may be performed using the appropriate interaction formula given in CEN/TS 1992-4 [8].

The comparison of the developed component model for the pinned joint with the respective experimental results is shown in Fig. 5. For this purpose, two specimens are used, one without and one with hanger reinforcement. The presented moment-rotation curves demonstrate a good agreement between results. It can be seen that the model can predict the contribution of the hanger reinforcement, for the resistance and ductility, in a satisfying way. The average approximation of the results, either for the case without hanger reinforcement either with, is very good. A maximum deviation of 4% is observed.



a) R2-C (without hanger reinforcement)



b) R2-C-R (with hanger reinforcement)

Fig. 5: M-φ curves comparing model and test results

4. Moment resisting joint of a composite beam to a reinforced concrete wall

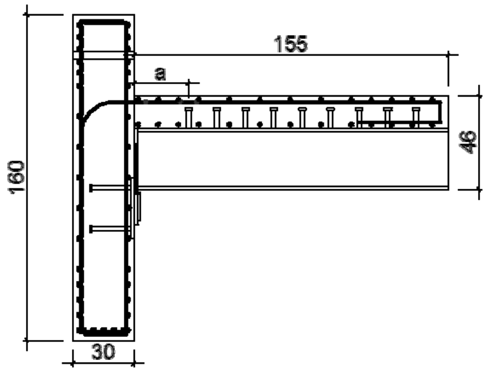
4.1 General description

In the studied moment resistant joint (see Fig. 1-c) two regions are distinguished. At the upper of the joint the connection, between the concrete slab and wall, is achieved extending and anchoring the longitudinal reinforcement of the slab in the wall. At the bottom part, the steel beam bottom flange sits in a steel bracket welded to an anchor plate. Using headed anchors, this plate performs the connection to the wall. Then, a contact plate, between steel beam and anchor plate, is used to transfer compression. In order to study the described joint configuration, experimental tests were executed within the experimental programme of the InFaSo research project [1]. In order to evaluate the joint properties to a hogging bending moment, a mechanical model, based on the component method, was developed and validated by the experimental results.

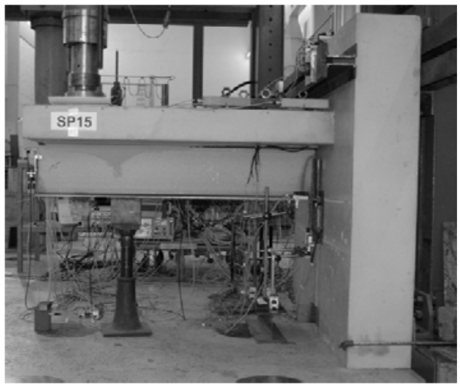
4.2 Experimental research

A total of six tests were performed, three at the University of Stuttgart and three at the Czech Technical University in Prague. In the first, the influence of the percentage of longitudinal reinforcement in the slab and the position of the first shear connector near the joint face were analyzed. In the latter, the thickness of the anchor plate and of the steel bracket was studied. The test layout is illustrated in Fig. 6. This consists in a cantilever composite beam supported by a reinforced concrete wall using the joint configuration described above. The loading is applied by a hydraulic jack at the free edge of the beam inducing the joint to a hogging bending moment. The loading is quasi-static monotonic.

In all tests failure was attained by rupture of one of the longitudinal steel reinforcement bars in the slab. The variations performed on the anchor plate and on the steel bracket, at the Czech Technical University in Prague, did not produce any significant influence on the behaviour of the joint. Thus, the longitudinal steel reinforcement governed completely the response of the joint. In Fig. 7 is shown the relative moment-rotation curves of the experiments executed in the University of Stuttgart. As expected, the joint resistance varied with the percentage of longitudinal reinforcement. The position of the first shear connector near the joint face affected the initial stiffness of the joint and mainly the ultimate rotation capacity.



a) Test specimens' configuration (cm)



b) Test layout

Fig. 6: Tests on moment resistant joint [12]

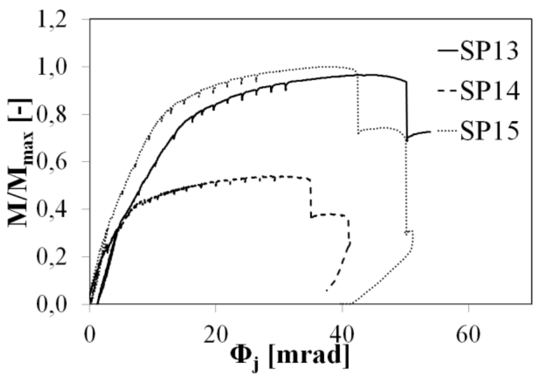


Fig. 7: Relative moment-rotation curves obtained in tests performed at the University Stuttgart

4.3 Analytical approach

Based on the joint configuration, the joint components activated are identified and the simplified model represented in Fig. 8 was developed. This reflects the joint mechanics when subjected to a hogging bending moment. As observed in the experimental tests, the longitudinal reinforcement in tension is the governing component. Consequently, the accuracy of the model will much depend on the level of sophistication introduced in the model of this component. A sophisticated model of the longitudinal reinforcement in tension may be found in [13] where the embedment of the bars in concrete is taken into account. In addition, the ultimate deformation capacity of the component can be performed allowing estimating the ultimate joint rotation capacity. In what concerns to the other components, as observed in the tests, their role on the joint response is minor. Thus, its evaluation was performed as prescribed in the EN 1993-1-8 [2] and EN 1994-1-1 [3]. For the group of compression components, components 5, 6 and 7, the T-stub in compression (column bases), prescribed by the EN 1993-1-8

[2], was used to evaluate their response. Some similarities were found between the behaviour of the group components and T-stub in compression. Then, in what regards the model assembly, the procedure used is similar as in the case of steel and composite joints. Establishing the joint lever arm (h_r) as the distance between the longitudinal reinforcement and bottom flange of the steel beam, the joint bending moment (M_j) and the joint rotation (Φ_j) may be determined as expressed in (4) and (5).

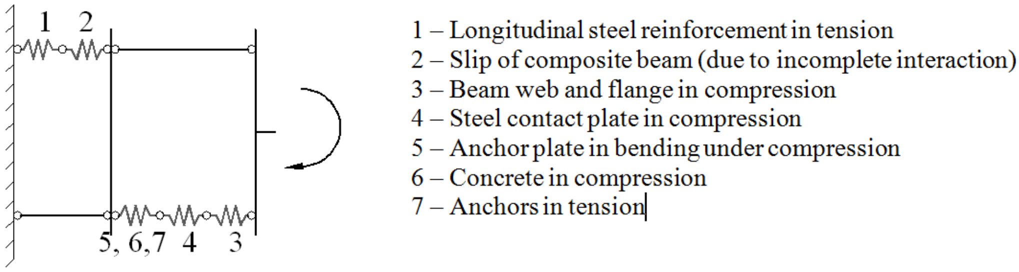


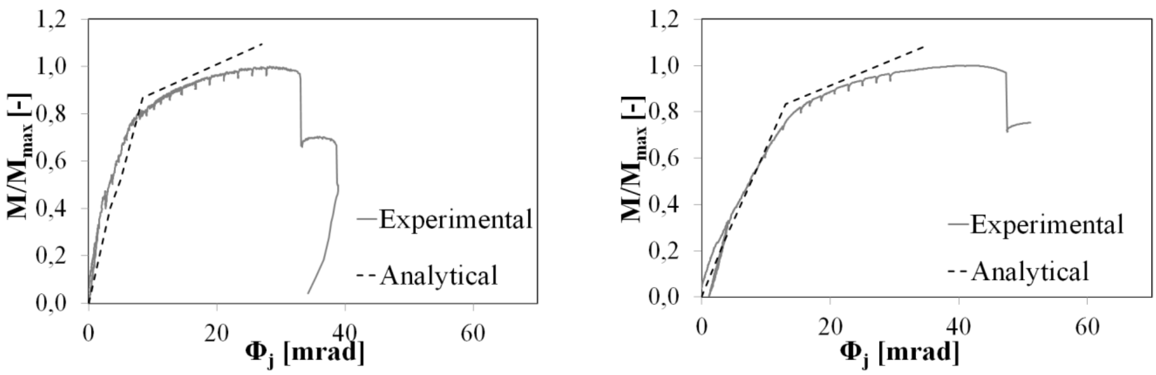
Fig. 8: Simplified mechanical model for the moment resistant joint

$$M_j = Min\{F_{eq,t}; F_{eq,c}\} h_r \tag{1}$$

$$\Phi_j = \frac{\Delta_{eq,t} + \Delta_{eq,c}}{h_r} \tag{2}$$

Where: $F_{eq,t}$ and $F_{eq,c}$ are the resistance of the equivalent components, tension and compression, respectively; $\Delta_{eq,t}$ and $\Delta_{eq,c}$ are the deformations of the equivalent components, tension and compression, respectively.

In Fig. 9 the relative moment-rotation curves comparing analytical model and experimental tests are shown. For this purpose, test specimens with different percentage of longitudinal reinforcement were used. As it can be observed a very good agreement was obtained for resistance, initial stiffness and hardening stiffness. The maximum deviation in terms of resistance was approximately 9%. In terms of ultimate joint rotation, taking into account the difficulty to find methods for its evaluation, the obtained approximation is interesting.



a) Test specimen SP14 (lower % percentage of reinforcement)

b) Test specimen SP15 (higher % of reinforcement)

Fig. 9: Relative moment-rotation curves comparing model and test results

5. Conclusions and outlook

In this paper a part of the work on pinned steel-to-concrete joints and the bending resistant composite joints within the RFCS research project "InFaSo" [1] has been presented. The project sought simple and efficient solutions to connect steel/composite members to reinforced concrete members. Within the project tasks, experimental tests were performed and analytical models developed for three types of joints: pinned joint, column base and moment resistant joint. The analytical models proposed, based on the component method, required the identification and characterization of "new" components related to the anchorage in concrete. Thus, based on experimental programme on components, analytical models for these components were proposed. At the joint level, the performed tests demonstrated interesting performance for both studied joint configurations, pinned and moment resistant. In the first case, the enhancement of the resistance and ductility was successfully achieved using hanger reinforcement in the anchor row in tension (on the non-loaded side). In the latter case, the joint configuration showed considerable bending moment resistance and joint rotation capacity. The derived component models showed to be accurate.

After the successful finalization of the "InFaSo" research project, a dissemination project InFaSo+, also funded by RFCS, will start in summer 2012. The aim is to disseminate the project's developments within workshops and seminars for practical engineers around Europe, also publishing Design Manuals in several languages in order to make the engineers more familiar with the component method for steel-to-concrete joints. Another important task is to prepare the project's results for standardization in order to include them into the Eurocode programme.

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