PEIKKO WHITE PAPER

COMPOSITE COLUMNS
CORBEL DESIGN VERIFIED

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DELTABEAM® FRAME

The DELTABEAM® Frame is a steel concrete composite frame solution which consists of DELTABEAM® Composite Beams, Composite Columns, and connections between the structural members. Most often other steel structures such as bracing systems are included in the delivery. Although the design process is utilizing a standardized selection of components, each structural member and connection detail of the DELTABEAM® Frame is tailored to suit the project in question.

BEAM TO COLUMN JOINTS

The flexibility and precision of the prefabricated steel components of the DELTABEAM® Frame allows for freedom in the architectural design. The variety of the shapes of frames sets high requirements for the joints between the structural members. The joints must not only fulfill the requirements of different design stages, but also be safe and easy to install.

The most common beam to column connection is nominally pinned. The definitive property of a beam to column connection varies from the construction stage to another, and from loading situation to another. From the load transfer point of view, the torsion resistance is a typically desired property in the construction stage, robustness in the accidental situation, and delayed temperature development in the fire situation respectively. For the normal stage, the design is principally defined by the vertical shear initiated by the support reaction from the beam. The vertical actions along a continuous column are transferred from the beam to the column by a variety of corbel arrangements. The load transfer to the composite section of the column is depending on the type of the corbel and possible shear devices.

EUROCODES AND LITERATURE

According to Eurocodes [1] in the regions of load introduction a clear load path should be defined. The amount of slip required to reach the defined load transfer should not be in contradiction with the design assumptions. In the case where the load is at first introduced to the steel section and then further to the composite section, the shear stresses should be evaluated from the sectional forces by elastic or plastic analysis.

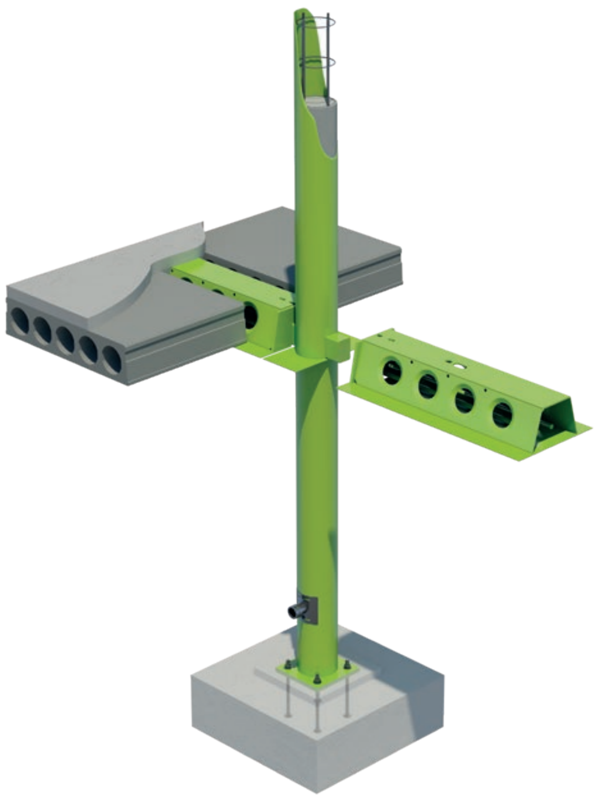

FIGURE 1 TYPICAL SECTION OF A DELTABEAM® FRAME

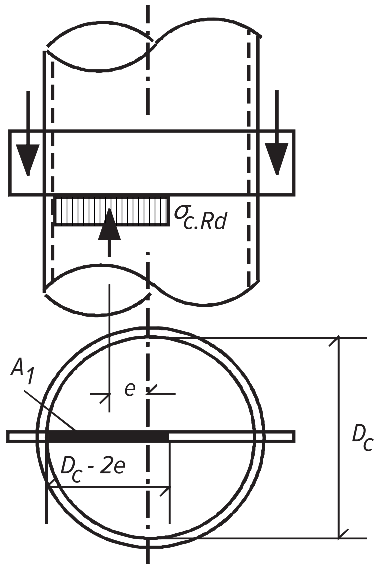

FIGURE 2 PRINCIPLES OF A GUSSET PLATE ARRANGEMENT AS GIVEN IN EUROCODE [1]

Shear connectors are required in the region of load introduction if the shear strength is exceeded at the steel concrete interface. The design shear resistance value is given as 0.40 MPa for rectangular and 0.55 MPa for circular hollow sections. The resistance values require that the steel surface in contact with the concrete is free from oil, loose scale and other impurities, which might have a negative effect on the shear action. The shear introduction length is defined so that it should not exceed 2d of L/3, where d is the minimum transverse dimension of the hollow section, and L is the column length.

In the case the shear resistance is exceeded, Eurocode suggests two types of solutions for arranging a mechanical shear connection. The simplest way is to add headed studs in the load introduction region where the studs may be designed as with composite beams. The second method is a so called gusset plate piercing the whole composite section (Figure 2). This solution is discussed as a plate corbel further in this paper.

With the plate corbel, the vertical reaction is distributed between the column profile and the concrete section underneath the plate. Due to partial loading, the local strength of concrete can be multiple times higher than the regular compressive strength of concrete. The strength of the connection between the plate and the column profile is not defined in the Eurocode, but the design can be adopted elsewhere from the literature. E.g. an analogy can be drawn to a gusset plate connection (Figure 3) defined in CIDECT Design guide 1 [2].

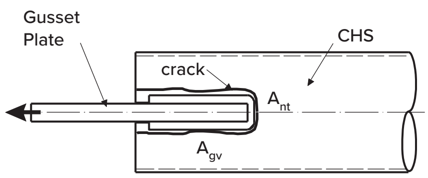

FIGURE 3 GUSSET PLATE CONNECTION DEFINED IN CIDECT DESIGN GUIDE [2]

TEST SERIES

INTRODUCTION

The scope of the test series was to broaden the knowledge regarding the load transfer behavior of a composite column in the vicinity of the load introduction. The main principles are available from the standards and from the literature, but design of an advanced joint requires assumptions which are critical to overall behavior. These tests were to examine those assumptions.

Where the preliminary tests concentrated on the principals of the shear transfer, the later tests with the corbels were to provide information about the behavior of a specific joint type. The specimens and the loading setup were planned so that they would represent a composite section taken out from a typical continuous multi story column.

The test series consisted of three different specimen types. The preliminary test series included only the type A specimen with direct load introduction (Figure 4a). The later test series included type A specimens as a reference, type B with surface corbel setup below (Figure 4b), and type C with plate corbel setup (Figure 4c) .

PRELIMINARY TESTS

Before the actual corbel tests, a relatively extensive study was arranged including specimens with direct loading (Figure 4a) to study the characteristic of the plain shear stress between the steel tube and the internal concrete. The aim of the study was to gather background knowledge and to define the most critical variables regarding the shear strength for planning the test series with corbels.

The preliminary study consisted of 13 groups with 4 identical specimens in each group, extending the total amount of specimens to 52. The steel tubes used for forming the specimens were selected so that they represent the variety of delivery conditions of several tube manufacturers. All steel tubes were circular, longitudinally welded and nominally graded as S355 structural steel. Prior to concreting the specimens, the dimensions and the material properties of the steel tubes were measured. Also, the condition of the internal surface was defined by the surface roughness tester and visually. Simultaneously with concreting the test specimens, a group of concrete specimens were cast to define the strength, the elastic modulus, and the shrinkage of the concrete. After concreting, all specimens were hermetically sealed to be opened at the moment of testing.

The following characteristics were varied between the series:

- tube diameter (139.6...406.4 mm) and wall thickness (4...10 mm);
- shear introduction length from 2 to 3 times the tube diameter;
- concrete grade (C30/37...C50/60);
- concrete age (28 and 365 d);
- internal surface of the steel tube (dry, oily, rusty).

The test loading was arranged so that the specimen was supported through the concrete section and the load was applied equally to the steel section. The loading was executed deformation controlled so that the slip reached 30 mm. The discussed slip was measured from the unsupported concrete surface i.e. the end of the specimen where the load was applied (Figure 4).

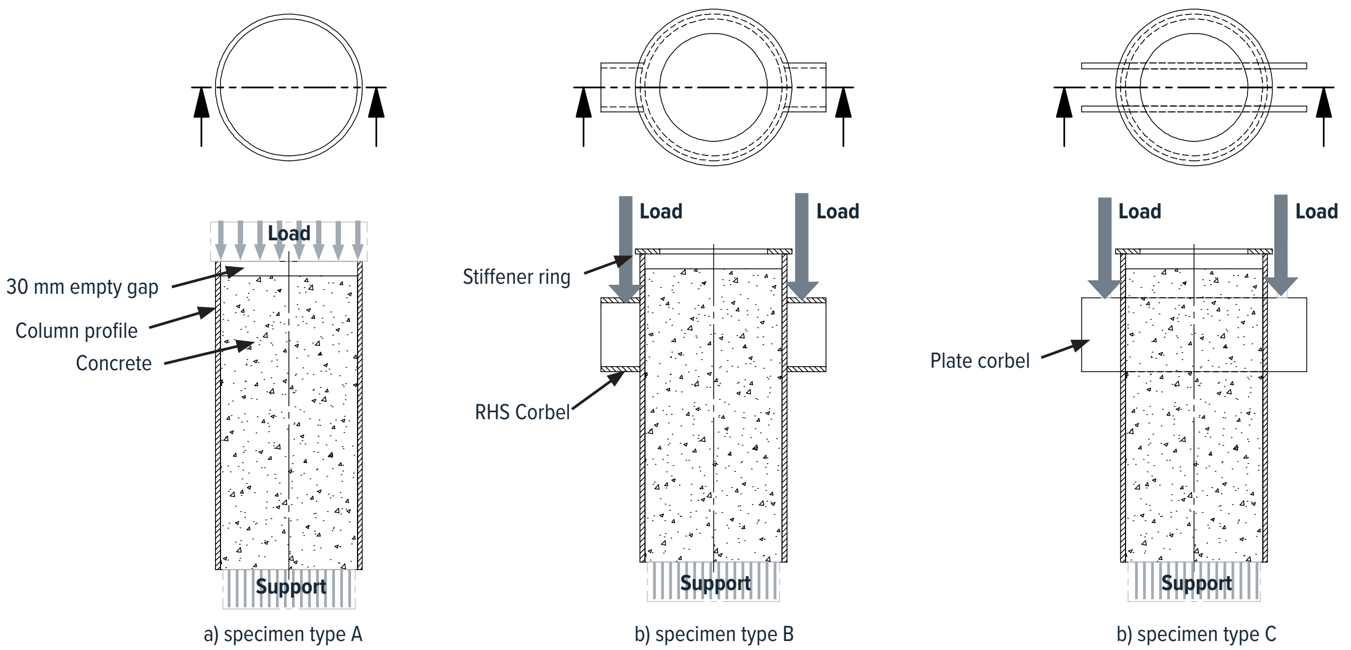

FIGURE 4 SPECIMEN TYPES

SUMMARY OF THE RESULTS

The size of the steel tube did not have an effect to the achieved shear stress within the tested tube range. Neither the material properties of concrete of steel did not show any effect to the shear stress levels. The shrinkage of the hermetically stored concrete specimens remained low (0.0076...0.0172%) and the ageing of the concrete did not have an effect to the achieved shear stresses or the effect of small shrinkage might be compensated by the also small increase in the concrete strength. The shear introduction length did not have a significant effect to the shear stresses and the difference can be assumed to be caused by the distributions of the longitudinal strains along the steel tubes.

Even though there were quite a lot of variation in the conditions of the internal surfaces especially when inspected visually the roughness did not show any significant effect to the shear stresses. Some series were formed so that the rolling oil from the tube manufacturing process was left on the internal surface and the shear stresses remained notably low. The relative difference of the stress-slip behavior of oiled and optimal surface is illustrated in the Figure 5.

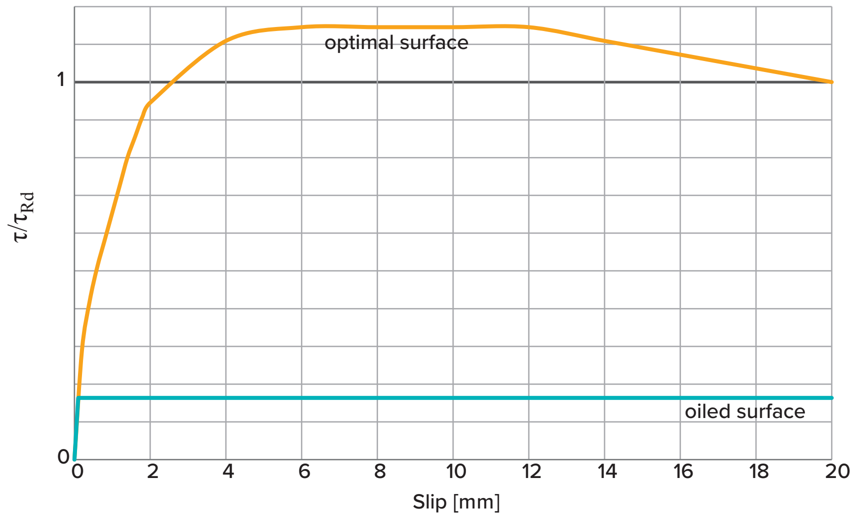

FIGURE 5 CHARACTERIZED SHEAR STRESS DEVELOPMENT AT THE INTERFACE BETWEEN THE STEEL TUBE AND CONCRETE CORE

CORBEL TESTS

The test with corbels were planned after the preliminary tests. The series consisted of 3 groups:

1. Reference group (3 specimens) with the same direct loading arrangement as in the preliminary study (Figure 4a).
2. Surface corbel group (4 specimens) – the corbels were formed by welding RHS profiles on the surface of the column steel tube (Figure 4b). The group differed from the reference group only by the load introduction as the load was now applied trough the corbels.
3. Plate corbel group (4 specimens) – the corbels were formed by plates placed throughout the column steel tube and the concrete section (Figure 4c). The external corbel section had similar dimensional properties with the corbels tested within the surface corbel group. Now the difference to the surface corbel group were the corbel plates embedded to the concrete section providing a mechanical connection towards the shear load.

The specimens within the three groups had the circular steel tubes with diameter of 323.9 mm and thickness of 6 mm. The steel tubes were cut from the same blank and the length was defined so that the length of the steel concrete interface could be set to 2 times the tube diameter. Before concreting the specimens, the internal surface of the steel tube was examined to be similar to the “oiled surface”, as discussed in the chapter related to preliminary tests.

All the specimens were cast from the same concrete patch which was defined and tested to be grade C30/37. The grade of all steel parts was nominally S355. After concreting, the specimens were hermetically sealed to be opened at the moment of testing after 28 days.

The loading was arranged identically with the preliminary tests with the exception with corbel specimens where the load was applied on the corbels. The eccentricity of the resultant of the load from the surface of the column was 30 mm and the length of the loaded area in the direction of the longitudinal axis of the corbel was 20 mm. This was to simulate the typical dimensions of a beam-to-column connection where the thickness of the beam end plate is 20 mm and the gap between the beam end plate and the surface of the column is also 20 mm.

FIGURE 6 SPECIMEN TYPE C UNDER TEST LOADING

SUMMARY OF THE RESULTS

The reference test with direct loading followed the outcome of the preliminary tests. The initial stiffness of the specimens with surface corbel was similar to what was experienced in direct loading (Figure 7). When the slip exceeded approx. 0.4 mm where shear stress development stopped with directly loaded specimens, the stress development continued until the end of the test (30 mm). The shear stress development with the surface corbel type can be assumed to be resulting from the corbels rotating due to the eccentric loading and causing a compression zone on the bottom end of the corbel. The slip reading includes also the deformations of the corbel but based on the low final deformations in the vertical direction, this can be ignored and slip readings of directly loaded specimens and specimens with surface corbel compared.

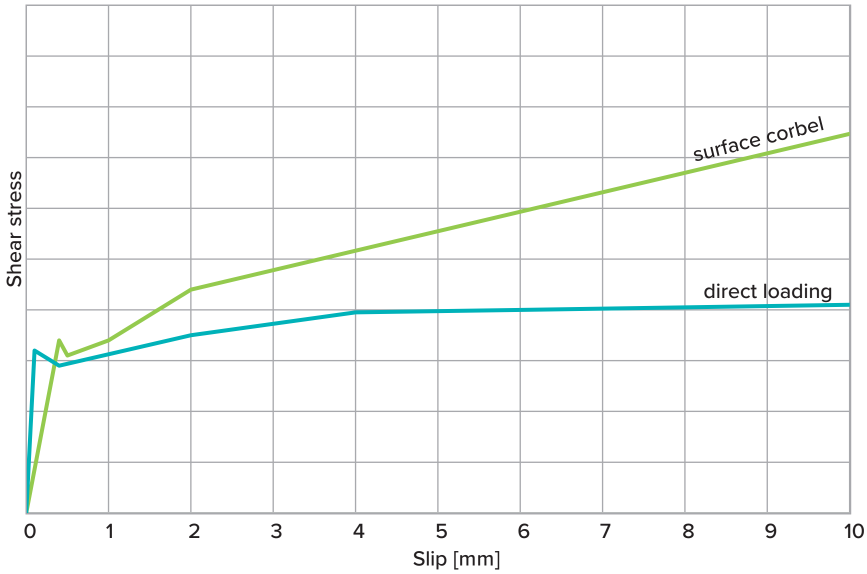

FIGURE 7 CHARACTERIZED STRESS SLIP CURVE OF THE SPECIMENS WITH DIRECT LOADING AND THE SURFACE CORBEL TYPE

With the plate corbel specimen type, the deformations were concentrated around the corbels, therefore the slip readings are not comparable to the other specimen types. The outer surface of the column steel tube was equipped with linear strain gauges and the most informative readings were taken from the gauges placed below the corbel measuring the vertical strain. The Figure 8 compares the measured strain to the total vertical deformation. Here the total deformation includes also the deflection of the corbels, whose significance increases when approaching the end of the loading.

The loading of the plate corbel specimens was stopped with lower deformations than when compared to two other specimen types. This was due to the load transfer from the corbels to the whole column cross section was stiffer than expected and load build up was mainly limited by the steel corbel itself.

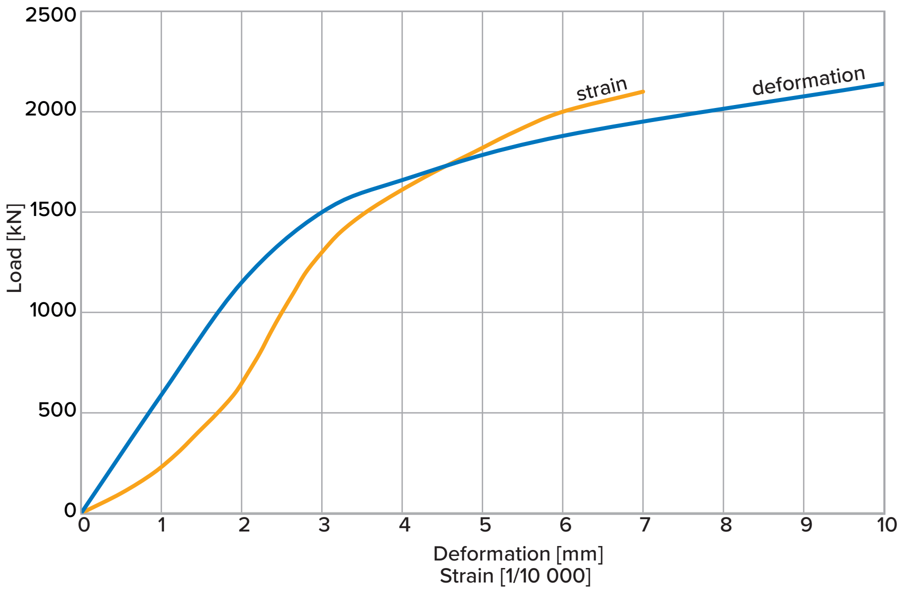

FIGURE 8 COMPARISON OF THE TOTAL DEFORMATION TO THE VERTICAL STRAINS MEASURED BELOW THE CORBEL

DISCUSSION OF THE STUDY

When an external action is to be transferred to a composite section, often the challenge is to activate the whole composite section. In the optimal situation, the introduced load can be distributed according to axial stiffnesses of the cross section members. With the plate corbel type of arrangement, where the piercing plate works as a stiff shear transferring device, this optimal state can be reached. The conditions in the concrete in the vicinity of the plate allow for the confining action and thereby high local stress of concrete.

The shear transfer based on adhesion and friction showed relatively large variance in the obtained shear stress levels, even though the shear interface met the cleanliness requirements. It may be that in the real structures the length of the active interface is longer than what is defined as the maximum length in the Eurocode.

The latest test series was in agreement with the assumptions regarding the plate corbel. The results, more precisely the strain readings, showed that the portion which is transferred directly to the concrete section is greater than assumed. The distribution of the load across the cross section is strictly dependent on the strains and here the stress strain relation of the concrete under the plate behaved stiffer than expected. The study highlights that to ensure the transfer of vertical shear forces in a safe and ductile manner, a level of mechanical shear connection is required at the interface between the column profile and the concrete. The transfer based on adhesion and friction is better suited for low forces from secondary structures.

REFERENCES

[1] EN1994 1 1:2004, Eurocode 4: Design of composite steel and concrete structures, Part 1: General rules and rules for buildings, CEN, 2004

[2] Design guide 1, For circular hollow section (CHS) joints under predominantly static loading, CIDECT, TÜV Verlag Rheinland, 1st edition, 1991

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