

## **EXPERIMENTAL DETERMINATION OF THE LOAD-BEARING BEHAVIOUR OF DRY JOINTS BETWEEN PRECAST ELEMENTS MADE OF UHPFRC**

**Werner Sobek (1, 2), Markus Plank (1), Dominique Corvez (3) and Karl-Heinz Reineck (1)**

(1) ILEK, University of Stuttgart, Germany

(2) Illinois Institute of Technology (IIT), Chicago, USA

(3) Lafarge, Paris, France

### **Abstract**

The application of ultra-high performance fibre reinforced concrete (UHPFRC) in structures entails in general the application of precast elements. Therefore the issue of how to join the elements is of highest importance. Dry joints allow the transfer of compression and shear forces, whereby the magnitude of the transferable shear force depends amongst others on the cohesion factor and the friction coefficient. Values for these are stated in the respective design codes depending on the roughness of the joint surface. However, the classification of the surface roughness is often not very exact so that an experimental verification of the cohesion factor and the friction coefficient is advisable.

Lafarge commissioned the Institute for Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart to carry out an experimental investigation to determine the effect of different surface roughness classes on the load-bearing behaviour of dry joints between precast elements made of UHPFRC.

### **Résumé**

L'application de BFUP structurel va généralement de pair avec l'utilisation de pièces préfabriquées. La question de leur mode de liaison se pose alors. Les « joints secs » permettent le transfert des efforts de compression et de cisaillement. L'intensité de l'effort tranchant transmissible dépend entre autres des facteurs de cohésion et des coefficients de friction. Ces derniers sont spécifiés dans les normes de conception respectives et dépendent de la rugosité de la surface en contact. C'est pourquoi la vérification du facteur de cohésion et du coefficient de friction est recommandée.

Lafarge a confié à l'ILEK (Université de Stuttgart) la réalisation d'un protocole expérimental pour déterminer l'effet de la rugosité de différentes surfaces sur la capacité et le comportement de transfert de joints secs entre des pièces préfabriquées réalisées en BFUP.

## **1. INTRODUCTION**

The application of ultra-high performance fibre reinforced concrete (UHPFRC) in structures entails in general the application of precast elements. Their production in an industrial plant enables a higher quality of the elements and improved mechanical properties of the material compared to the application of UHPFRC on site. The reasons for this are due to the production process:

- mixing: the material components can be weighed precisely and the strictly defined mixing procedure can be adhered to;
- casting: a highly precise formwork ensures a higher dimensional accuracy of the precast elements and the casting methodology can be optimized to achieve a desired fibre orientation within the precast elements;
- curing: after stripping the formwork the precast elements can be subjected to heat treatment to accelerate the attainment of the final strength, reduce creep and shrinkage and improve the durability of the material.

In precast construction joining technologies play a dominant role and have to fulfil the following general requirements [1]:

- transfer of forces;
- coupling of deformations;
- assembly, disassembly and recyclability;
- thermal coupling;
- acoustic coupling;
- contact corrosion.

Most importantly the joining technology has to ensure that the forces are transferred from one element to the other and ideally also enables the elements to be assembled and disassembled in an easy way. These requirements can be achieved by either point connections [2, 3] or continuous connections.

Continuous connections can be realized by tensioning concrete elements together with a dry joint between the elements. Thereby the dry joint is subjected to a compression force whose presence enables the transfer of a shear force through mechanical interlock and friction from one element to the other.

In design codes cohesion factors and friction coefficients between concrete elements are given depending on the roughness of the joint surface. However, the classification of the surface roughness of interfaces or joints is often not very exact so that an experimental verification of the cohesion factor and the friction coefficient is advisable.

## **2. TEST PROGRAMME**

The test programme was designed to determine the effect of different surface roughness classes on the load-bearing behaviour of dry joints. The following surfaces were tested:

- plain surface (cast against PE 500);
- sand blasted surface;
- indented surface – layout 1 (cast against PE 500);
- indented surface – layout 2 (cast against PE 500).

4 specimens were tested for each surface roughness, i.e. 16 tests were carried out in total. The joint tests were performed as push-out tests and were displacement controlled. The

compression force normal to the joint surface was 57 kN which is equivalent to a compressive stress of 6 MPa.

The test programme was complemented by control tests for the compressive strength and the bending tensile strength of the UHPFRC used.

### 3. PRODUCTION OF TEST SPECIMENS

#### 3.1 Material

The UHPFRC used for the experimental investigation was *Ductal® FM Grey, formulation 2GM2.0*, from Lafarge. The steel fibres had a length of 14 mm and a diameter of 0.185 mm and were added at a ratio of 2.0 % by volume.

#### 3.2 Casting and curing

Due to the configuration of the test setup each test specimen consisted of three elements, i.e. a middle element and two side elements. This resulted in two joint surfaces per test specimen whereby both had the same roughness. The geometry of the test specimens is shown in Figures 1 to 3. All middle elements had a depth of 110 mm, whereas all side elements had a depth of 100 mm. The surface area in each of the two joints was 95 mm x 100 mm.

The formwork was such that each element of the test specimens was cast individually and each joint surface was cast against PE 500. After stripping the formwork the test specimens were heat-treated for at least 48 hours at a temperature of approximately 90 °C.

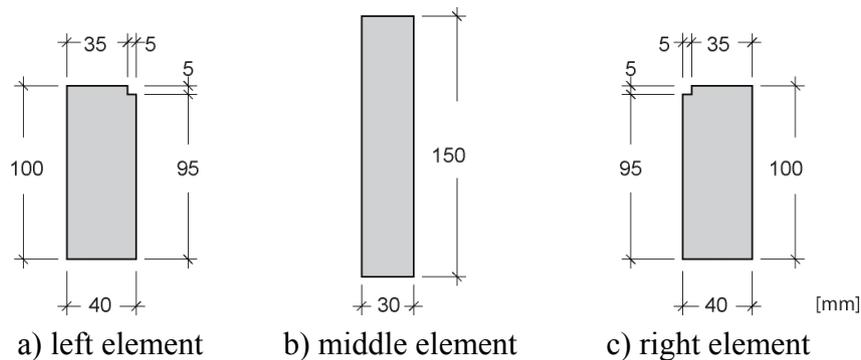


Figure 1: Geometry of test specimens with plain and sand blasted surface

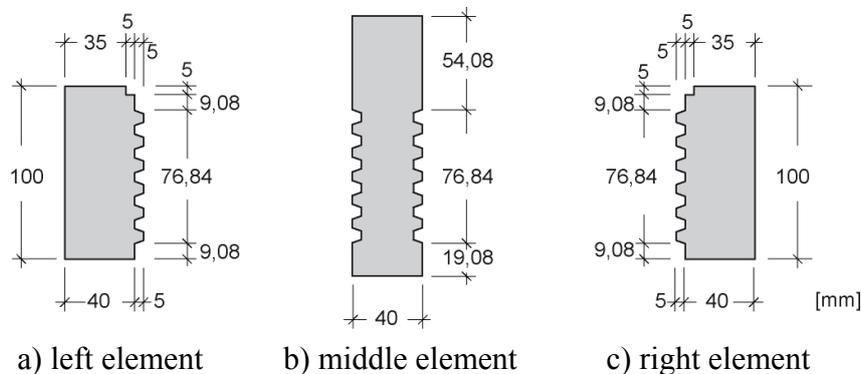


Figure 2: Geometry of test specimens with indented surface (layout 1)

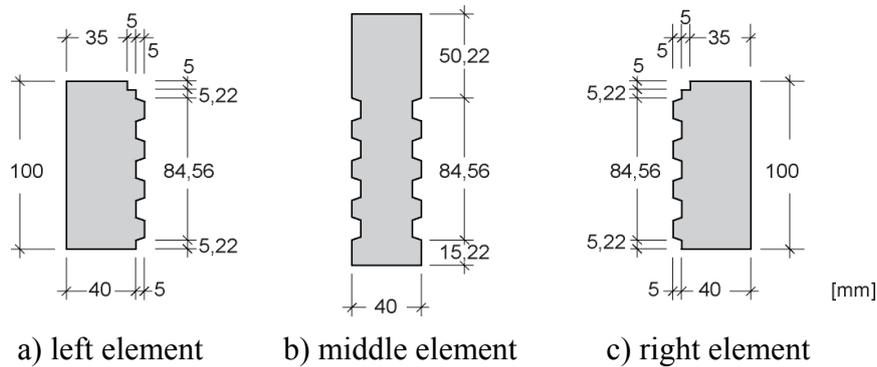


Figure 3: Geometry of test specimens with indented surface (layout 2)

### 3.3 Classification of surface roughness

According to [4, 5] the surface roughness of interfaces or joints is classified as “very smooth”, “smooth”, “rough” or “indented”.

Surfaces cast against plastics can be classified as “very smooth” such as a plain surface cast against PE 500. Sand blasting is an often used method to roughen concrete surfaces. Within the limits of the experimental investigation several abrasive materials such as sand, steel and corundum were tested regarding their effect on a surface made of UHPFRC. The best result was achieved by using corundum with a grain size between 1 and 2 mm at a pressure of 6.5 bar (0.65 MPa). Thereby the surface got more roughened than by using sand grains and the steel fibres were less exposed than by using steel grains as an abrasive material. The achieved roughness was then measured according to the sand patch method after Kaufmann [6]. However, due to the smoothness of the surface the average roughness  $R$  was difficult to determine and amounted to 0.072 mm, which is practically negligible. Thus the sand blasted surface can be classified as “very smooth”.

The “indented” surfaces were tested in two different layouts as shown in Figure 4. In layout 1 (Figure 4a) the ratio between the length of the tooth crown and the tooth height is 1:1 whereas in layout 2 (Figure 4b) the ratio is 2:1. In both layouts the tooth flank is inclined  $20^\circ$  normal to the indented surface. With respect to layout 2 it should be noted that the parameters describing the geometry are based on theoretical and experimental investigations regarding the optimum configuration of an indentation made of steel for a continuous introduction of compression forces into concrete structures [7, 8].

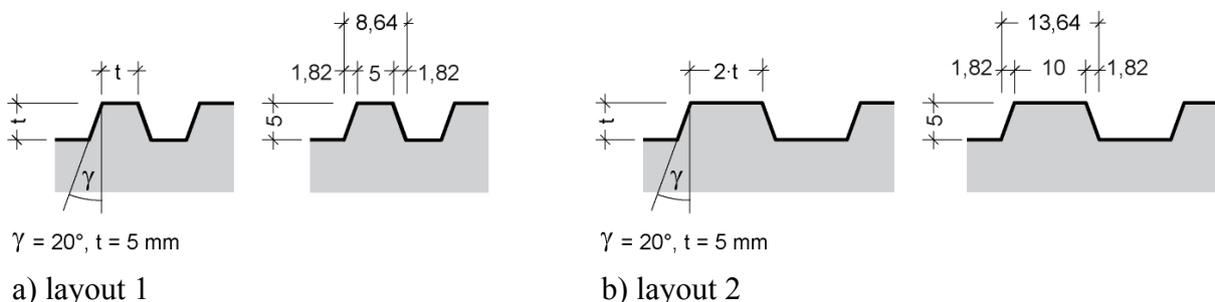


Figure 4: Parameters and geometry of the two tested indentation layouts

#### 4. EXECUTION OF TESTS

The joint tests were performed as push-out tests (Figure 5). The side elements of the test specimen were supported on steel plates of which one was fixed and the other was horizontally displaceable. The middle element of the test specimen was clamped between the two side elements by a defined compression force that acted normal to the dry joints.

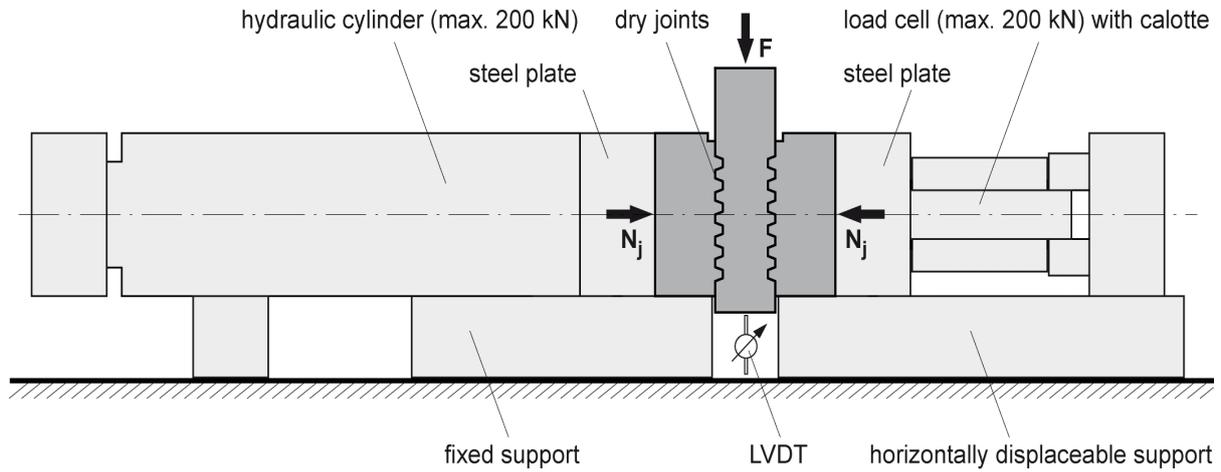


Figure 5: Test setup for joint tests (schematic)

The tests were displacement controlled at a rate of 0.1 mm/min up to 1.0 mm/min. During the test the piston of the testing machine exerted a vertical load onto the middle element of the test specimen that resulted in a displacement in the direction of the load. The relative displacement between the middle element and the side elements was measured with two linear variable differential transformers (LVDT).

#### 5. EVALUATION OF TESTS

##### 5.1 Mohr-Coulomb failure criterion

Due to the configuration of the test setup the test specimens had two joint surfaces. The shear force per joint was calculated as follows:

$$V_j(s) = 0.5 \cdot F(s) \quad (1)$$

with  $V_j(s)$  shear force per joint as a function of displacement  
 $F(s)$  test load as a function of displacement  
 $s$  displacement

For the further evaluation of the tests the Mohr-Coulomb failure criterion was used. It describes a linear relationship between the shear stress and the compressive stress at failure:

$$\tau_{j,max} = \frac{V_{j,max}}{A_j} = c \cdot f_{cc} - \mu \cdot \sigma_j \quad (2)$$

with  $\tau_{j,max}$  maximum shear stress per joint  
 $V_{j,max}$  maximum shear force per joint  
 $A_j$  surface area per joint

$c$	cohesion factor
$f_{ct}$	tensile strength of concrete
$\mu$	friction coefficient
$\sigma_j = \frac{N_j}{A_j}$	stress normal to joint surface
$N_j$	force normal to joint surface (<0 compression force)

## 5.2 Behaviour of dry joints with “very smooth” surfaces

The force-displacement curves of the test specimens with plain surfaces are shown in Figure 6 and those with sand blasted surfaces in Figure 7. Thereby the shear force per joint is plotted upwards and the compression force is plotted downwards against the displacement.

The mean value of the maximum shear force that could be transferred across the dry joints with plain surfaces amounted to 44.26 kN ( $F_{jmax} = 4.61$  MPa) compared to 37.12 kN ( $F_{jmax} = 3.87$  MPa) that could be transferred across the dry joints with sand blasted surfaces. In comparison, the design shear resistance for a “very smooth” surface amounts to 3.00 MPa when calculated according to [4, 5]. Therein the values for the cohesion factor and the friction coefficient are given with 0 and 0.5, respectively. The partial safety factor for the compressive stress normal to the joint surface was taken as 1.0.

The results show that sand blasting the surface has an adverse effect on the load-bearing behaviour of dry joints. This was also reported by other researchers [9, 10] and explained as follows:

- sand blasting reduces the contact area between the elements and creates macroscopic cones and rills on the surface;
- the application of a compression force causes high stress concentrations at punctual contacts between the macroscopic cones and rills;
- the application of a shear force and the subsequent displacement shears the microscopic cones and rills off;
- the attrition material reduces the friction between the surfaces.

Since for dry joints with “very smooth” surfaces the mechanical interlocking is negligible the friction coefficient can be calculated as follows:

$$\mu(s) = \frac{V_j(s)}{-N_j(s)} \quad (3)$$

with  $\mu(s)$  friction coefficient as a function of displacement  
 $N_j(s)$  force normal to the joint surface as a function of displacement  
 (<0 compression force)

The mean value for the friction coefficient of plain surfaces amounts to 0.77 and that for sand blasted surfaces to 0.65.

It should be noted that the deformations of the dry joints with sand blasted surfaces were higher compared to the dry joints with plain surfaces as the mean value of the displacement corresponding to the maximum shear force amounts to 0.45 mm for sand blasted surfaces and to 0.27 mm for plain surfaces.

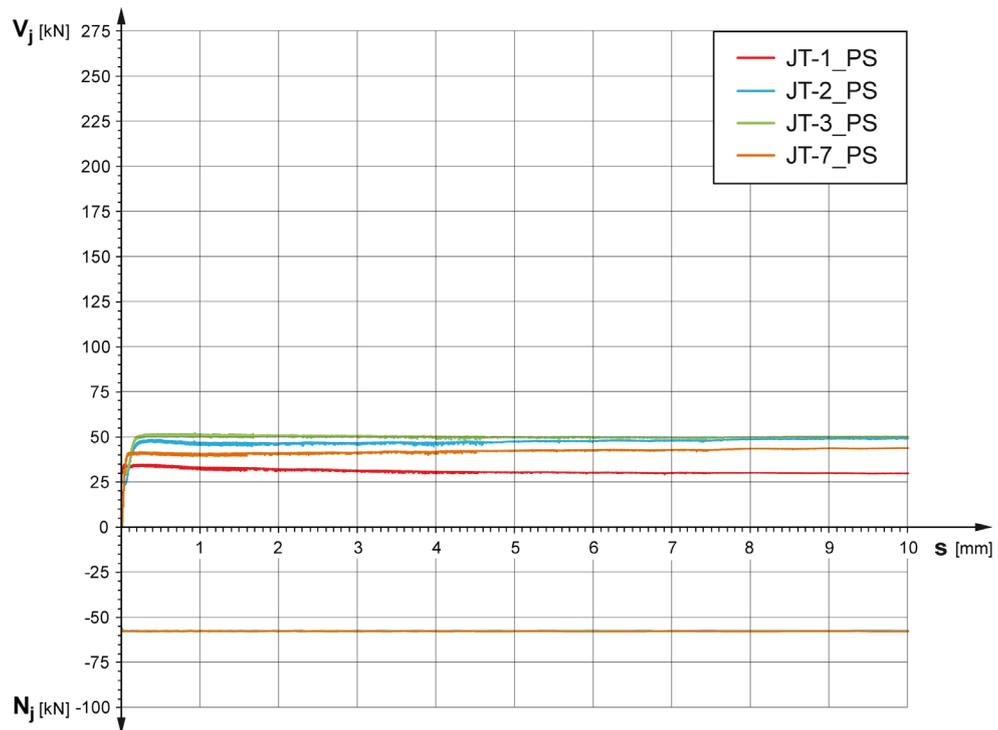


Figure 6: Force-displacement curves of 4 test specimens with plain surfaces

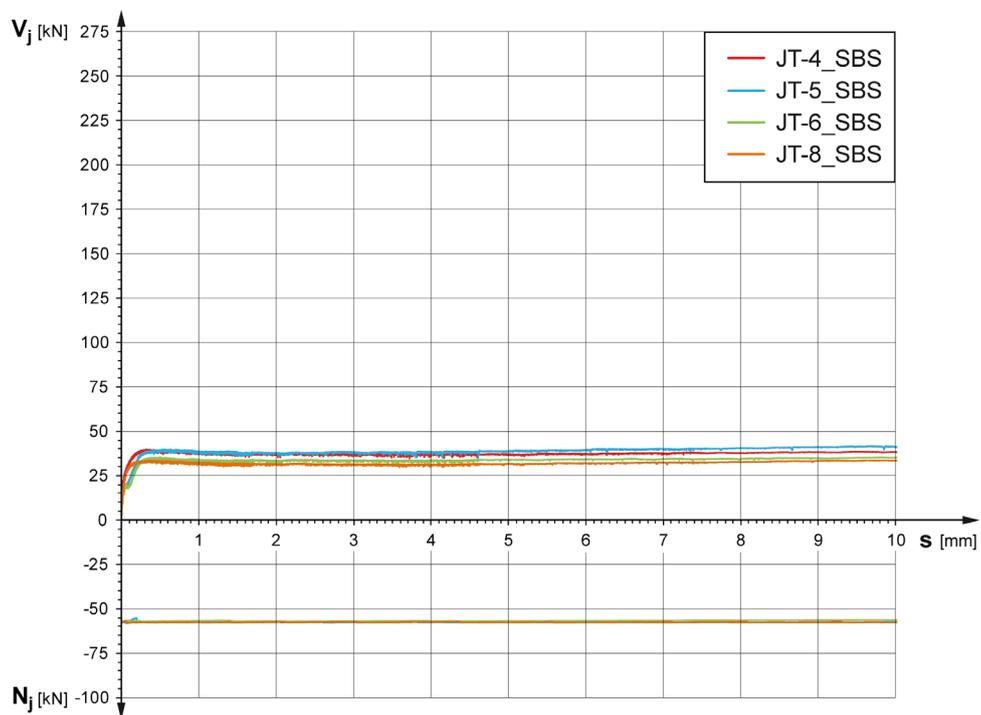


Figure 7: Force-displacement curves of 4 test specimens with sand blasted surfaces

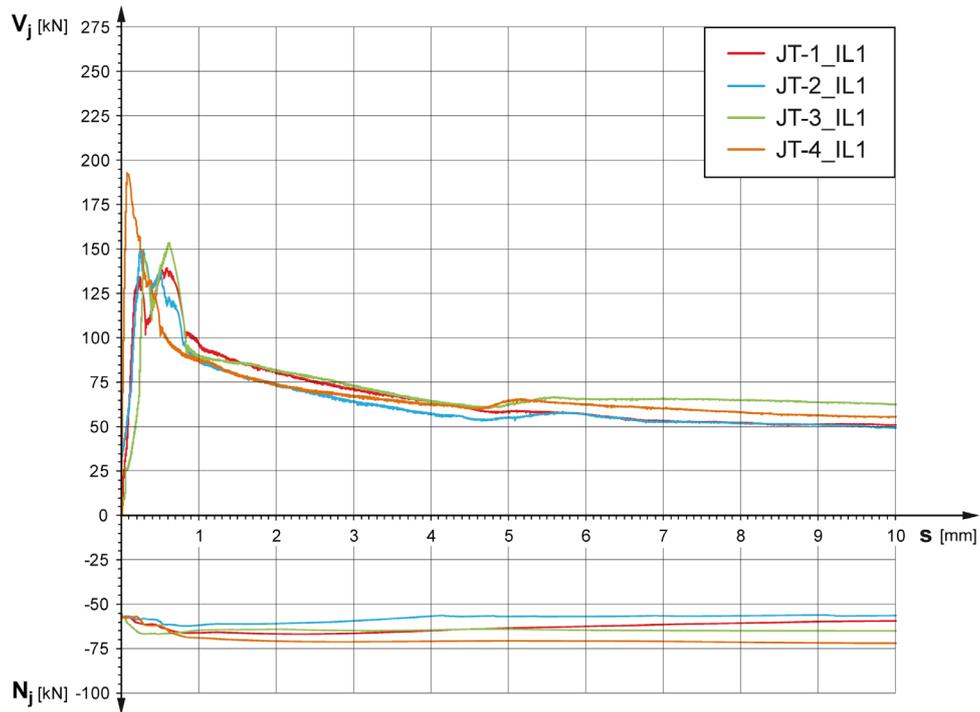


Figure 8: Force-displacement curves of 4 test specimens with indented surfaces (layout 1)

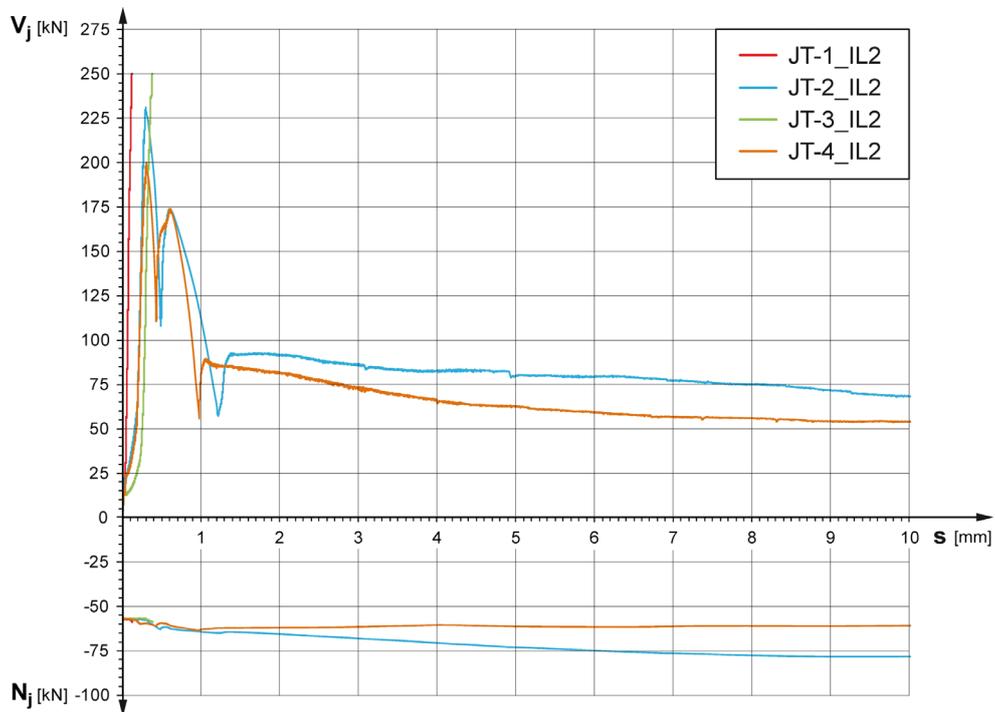


Figure 9: Force-displacement curves of 4 test specimens with indented surfaces (layout 2); test specimens JT-1\_IL2 and JT-3\_IL2 did not fail up to a shear force of 250 kN per joint when the maximum test load of testing machine was reached

### 5.3 Behaviour of dry joints with “indented” surfaces

The force-displacement curves of the test specimens with indented surfaces are shown in Figure 8 for layout 1 and in Figure 9 for layout 2.

Comparing the load-bearing behaviour of the dry joints with indented surfaces shows that layout 1 transferred significantly lower shear forces per joint than layout 2; the mean values for the maximum shear force were 155.58 kN ( $F_{j,max} = 16.38$  MPa) compared to 232.77 kN ( $F_{j,max} = 24.50$  MPa). It should be noted that two test specimens with layout 2 did not fail up to a shear force of 250 kN per joint when the maximum test load of the testing machine was reached. However, the formation of cracks indicated an imminent failure why for the two test specimens a maximum shear force of 250 kN was assumed for the calculation of the mean value. In comparison, the design shear resistance for high strength concrete (C90/105) with an “indented” surface amounts to 6.39 MPa when calculated according to [4, 5]. Therein the values for the cohesion factor and the friction coefficient are given with 0.5 and 0.9, respectively. The partial safety factor for the compressive stress normal to the joint surface was taken as 1.0.

For both layouts the formation of cracks at the root of the teeth of the side elements indicated an imminent failure. At failure of a tooth it came to an abrupt and steep decrease in the shear force. A further decrease in the shear force occurred when further teeth failed. With increasing displacement all teeth of the side elements were eventually sheared off. In addition a slight increase in the compression force could be observed which indicates a displacement normal to the dry joint, i.e. an opening of the dry joint.

For the determination of the friction coefficient further tests with a different compression force are necessary to obtain further combinations of compression and shear forces that lie on the linear slope of the Mohr-Coulomb failure criterion.

## 6. CONCLUSIONS

A series of tests was conducted to study the effect of different surface roughness classes on the load-bearing behaviour of dry joints between precast elements made of UHPFRC.

It was observed that sand blasting of surfaces made of UHPFRC does not lead to the surfaces being classified as “smooth” or “rough” according to [4, 5]. Furthermore, it has an adverse effect on the load-bearing behaviour as the friction coefficient is lower and leads to higher deformations compared to dry joints with a plain surface. This was also observed by other researchers [9, 10].

The parameters describing the geometry of the indentation according to layout 2 are based on theoretical and experimental investigations regarding the optimum configuration of an indentation made of steel for a continuous introduction of compression forces into concrete structures [7, 8]. It became evident that dry joints with this very layout allow the transfer of significantly higher shear forces than dry joints with an indentation according to layout 1. In both cases it was observed that the teeth of the side elements did not fail simultaneously but consecutively.

The experimental investigation showed that for the chosen compressive stress of 6 MPa dry joints with indentations can transfer a 3.55 up to 6.33 times higher mean shear stress than dry joints with a surface classified as “very smooth”. In comparison, the design shear resistance for high strength concrete (C90/105) calculated according to [4, 5] is 2.13 times higher when the surface of the dry joints is classified as “indented” instead of “very smooth”.

## ACKNOWLEDGEMENTS

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