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WHITE PAPER

SHEAR TRANSFER IN PEIKKO BOLTED CONNECTIONS

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Jaakko Yrjölä M.Sc.
Senior Manager,
Sustainability & Research
Peikko Group Corporation

Jan Bujnak
Vice President,
Product Development
Peikko Group Corporation

FOREWORDS

Bolted connections provide a quick and efficient means of joining precast concrete elements together, resulting in a structurally sound and durable building..

One of the primary benefits of bolted connections in precast structures is their versatility. Bolted connections can be used to join precast concrete elements together in a wide range of configurations, including column-to-foundations, column-to-column and beam-to-column joints. This allows for greater flexibility in the design of precast structures, making it possible to create complex geometries and unique shapes that would be difficult or impossible to achieve with cast-in-place concrete.

Another advantage of bolted assemblies is their ease of installation. Because the connections are prefabricated and standardized, they can be quickly and easily installed on site, reducing the need for specialized labour and equipment. This results in faster construction times and lower overall costs.

Bolted connections also offer superior durability compared to other types of connections. The high-strength bolts used in these connections can withstand significant forces and loads, ensuring the long-term integrity and safety of the structure. Additionally, because the connections are prefabricated, they are less susceptible to the variability and inconsistencies that can occur with cast-in-place concrete, which can help to reduce the risk of structural failure over time.

Finally, because the connections can be easily disassembled and reused, they allow for greater flexibility and adaptability in the use of the buildings. This means that precast structures can be easily modified or expanded as needed, reducing the need for new construction and minimizing waste.

In conclusion, bolted connections are an essential component of precast concrete structures, offering a range of benefits including versatility, ease of installation, durability, and sustainability.

Peikko provides several unique solutions for connecting precast structures or creating steel-to-concrete assemblies on the construction site. The product portfolio of bolted connections includes different types of anchor bolts, anchor bolt couplers and column or wall shoes (see *Figures 1* and *2*).

Figure 1. BOLDA® Column shoe (left) and set of COPRA® Anchoring couplers (right).

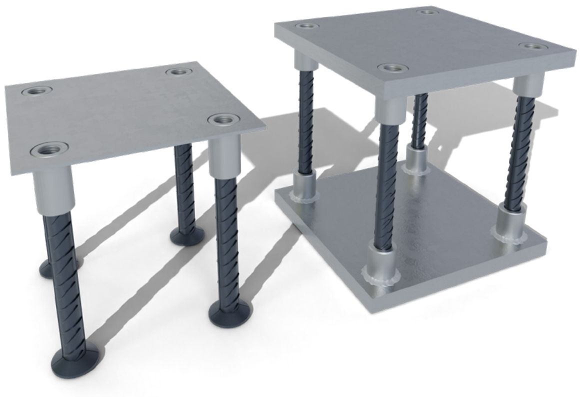

Figure 2. THRELDA® Anchor plate.

Depending on the specific joint conditions and requirements, the assemblies either have a grouted gap between the two connected elements (typically in precast column assemblies) or are executed without a gap (typically a steel profile fastened flush on the load-bearing concrete member) as presented in *Figure 3*. If a gap is present, it must be grouted with cement-based mortar on site to secure the load transfer through the connection.

While being slightly different, the assemblies serve a similar purpose: transfer forces from one structure to another through the connection. Bolted connections are subjected to shear and normal forces or their combination (*Figure 4*).

Figure 3. Bolted precast column connection with a gap (left) and a connection between a steel member and THRELDA® Anchor plate (right).

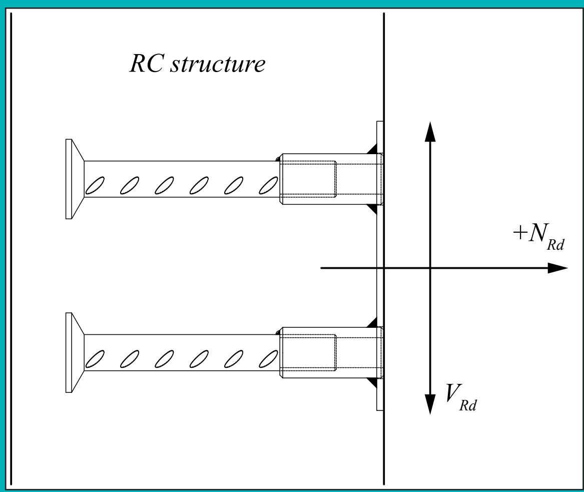

Figure 4. Acting loads on THRELDA® Anchor plate.

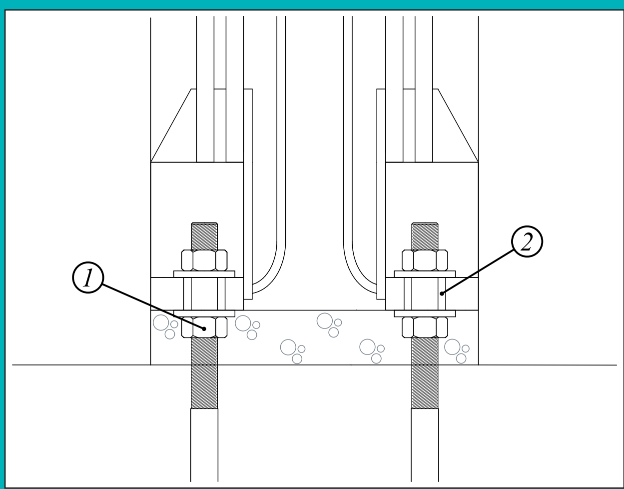

Figure 5. Connection detail of bolted precast column connection.

INTRODUCTION

Bolted connections show ductile behaviour under shear loads, enabling them to withstand high ultimate shear forces [1]. Such loads are typically associated with large transverse deformations, which are often not tolerable in practice. Based on the current standards, structures and their connections should retain an adequate appearance in the serviceability limit states [2]. The maximum service load through the bolted connection should thus be limited to avoid inelastic behaviour of the joint, which can namely happen through yielding of the steel part, cracking of concrete or slip of the connected structure related to anchor bolts. In practice, it is necessary to secure that the behaviour of the connection remains linear and reversible under service loads [3].

The state-of-the-art knowledge implies that shear transfer in bolted connections is secured either by friction forces or through doweling effect of bolts [4].

Building components, such as beams, columns, and walls, always require sufficient amount of installation tolerance on site. Without providing tolerance, the installation of such structures becomes ineffective or even impossible. In general, concrete structures require bigger tolerances than steel structures, which can be manufactured with higher precision. Bolted connections for precast structures are characterized by adjustment nuts for levelling the assembled structure ① and oversized bolt holes for allowing easy installation ② (see *Figure 5*). While column shoes for precast columns are provided with a hole clearance about +/- 5 mm, it is recommended to use +/- 2 mm hole clearance for steel structures connected with THRELDA® Anchor plates.

This paper presents results of shear tests of columns connections made with HPKM® Column shoes and shear tests for steel to concrete assemblies made with THRELDA® Anchor plates. The tests were planned to demonstrate the shear transfer mechanisms, which limit the maximum shear force through the connections in the serviceability limit states.

SHEAR TESTS OF BOLTED PRECAST COLUMN CONNECTIONS

A total of four tests were completed by connecting precast columns 350 × 350 × 1500 mm with foundation structures 450 × 700 × 1400 mm, having a 50 mm wide grouted gap (C50/60) between the structures (see *Figure 6*). Columns were equipped with four HPKM® 16 Column shoes [5] and four HPM® 16 Anchor bolts [6] or COPRA® 16 H Anchoring couplers [7] were anchored inside the foundation. Recess boxes of column shoes were not grouted to enable the dismount of columns.

Figure 6. Test setup of one of the shear tests.

In the tests the transverse load P was applied by a hydraulic actuator. Displacements of column end above grout pad (d) were measured with two linear variable differential transducers (LVDT) from both sides of the column and mean value is used for further evaluations. The foundation structures were laid on a strong floor and the other end of the columns were freely supported. *Figure 7* show schematically the test setup of the shear tests.

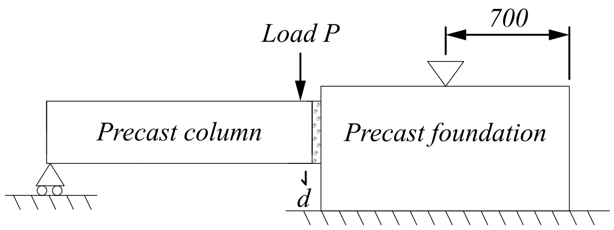

Figure 7. Schematic Diagram of the Shear Test Setup.

Strain gauges were also glued to threads of Peikko Anchor Bolts (see *Figure 8*). They were registering tensile and compressive strains of the threads under increasing actuator load.

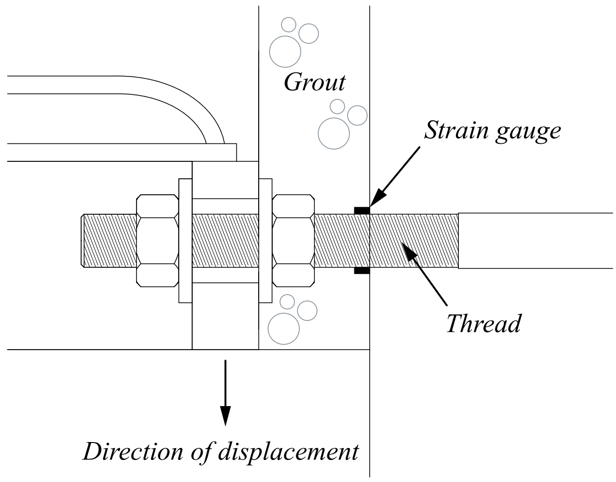

Figure 8. Strain gauges on threads.

Cubic strength of precast and grout concrete was measured by standard sized test cubes. In two test setups, joints between the grout and the precast structures were treated with a release agent. This was done to reduce the bond between the two concrete layers and enhance the demountability. Key parameters for each test are given in *Table 1*.

Table 1. Key parameters in shear tests.

Test number	Bolt type	Thread grade	Release agent	Grout f_{cube} [MPa]	Column f_{cube} [MPa]	Foundation f_{cube} [MPa]
03	HPM 16	B500B	-	59.0	77.4	72.7
01	COPRA 16 H	8.8	-			
01-Oil	COPRA 16 H	8.8	Oil			
02-Plate	COPRA 16 H	8.8	Thin plates			

Measured transverse load-displacement relationships are presented in *Figure 9*. While the ultimate load in tests with HPM® 16 Anchor bolts was ~ 410 kN and was associated with significant displacement, shear tests with COPRA® 16 H Anchoring couplers and threaded bars ended up with ultimate load ~ 300 kN and smaller displacement. All connections behaved similarly and showed an almost linear load-displacement relationship until a load level ~ 40 kN.

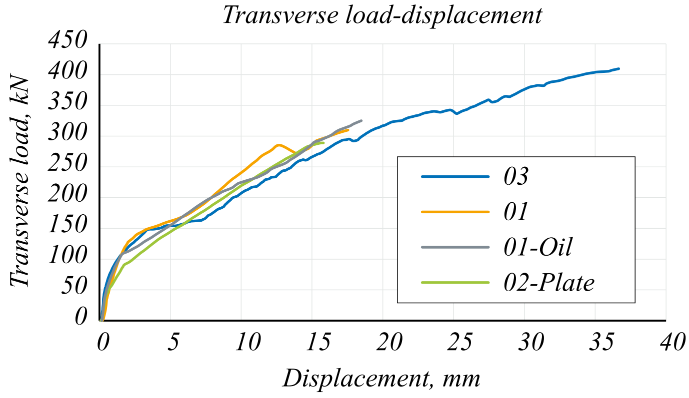

Figure 9. Transverse load-displacement relationships.

BENDING TESTS OF BOLTED PRECAST COLUMN CONNECTIONS

A total of six tests were conducted by connecting precast columns measuring 350 × 350 × 1500 mm with foundation structures of 450 × 700 × 1400 mm, and having a 50 mm grouted gap (C50/60) between the structures (see *Figure 10*). Columns were equipped with four HPKM® 16 Column shoes [5] and four COPRA® 16 H Anchoring couplers [7] were anchored inside the foundation. Also here, the recess boxes for column shoes were not grouted.

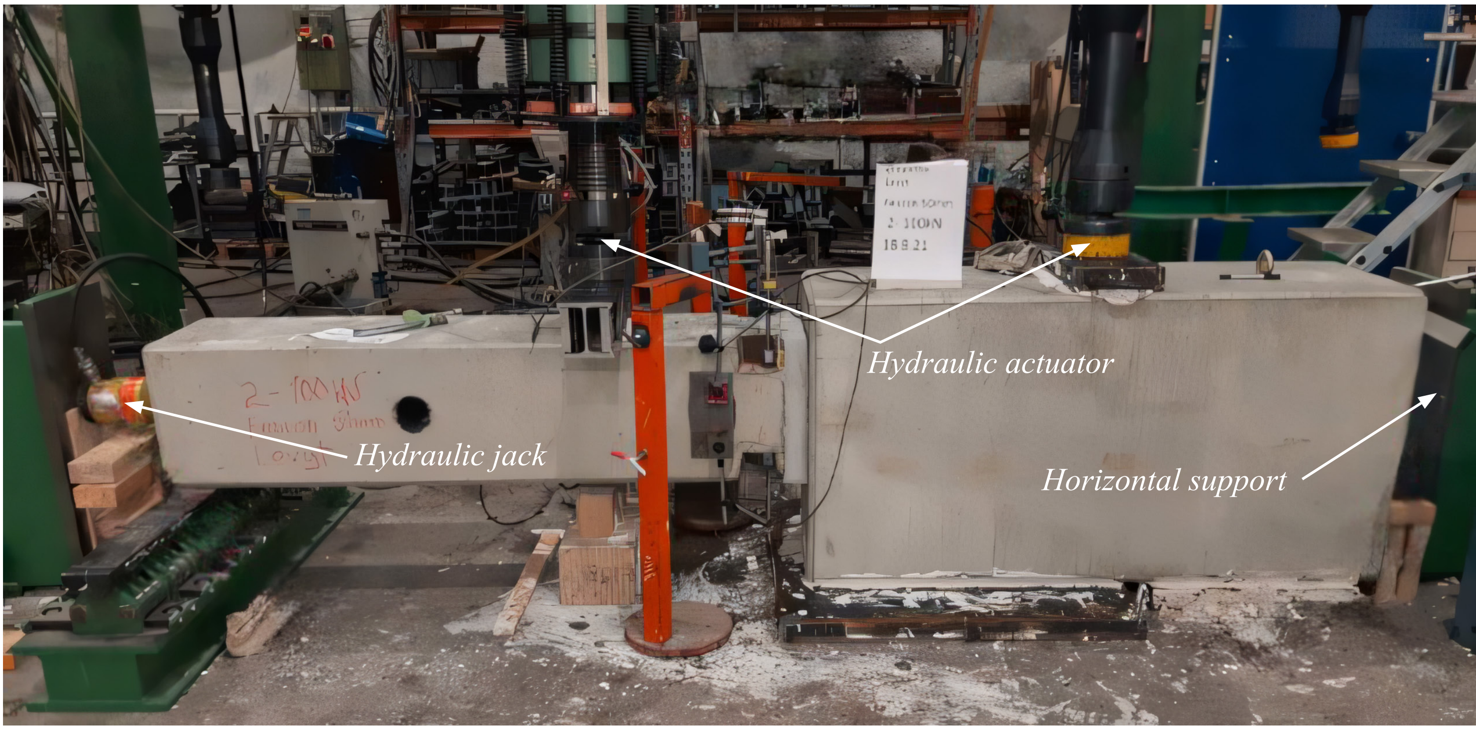

Figure 10. Test setup of one of the bending tests.

In the tests, the transverse load P was applied by the hydraulic actuator with the lever arm of 500 mm (*Figure 11*). A constant horizontal load F was applied on the column end and the foundation was supported in horizontal direction. The foundation structures were laid on strong floor. Displacements of column end above grout pad (d) were measured with two LVDTs from both sides of the column and mean value is used for further evaluations. *Figure 11* shows schematically the test setup of the bending tests.

Strains of the threads were not measured in the bending tests, but focus was paid on slip between the column shoes and anchor bolts. This was done by applying four additional LVDTs on anchor bolts inside the oversized bolt holes. The nuts of the bolts were initially tightened by a torque of 150 Nm, which was considered as an average from recommended minimum and maximum torque according to Peikko's technical manual for Column Shoes [5]. Measured concrete strengths and key parameters for each test are given in *Table 2*.

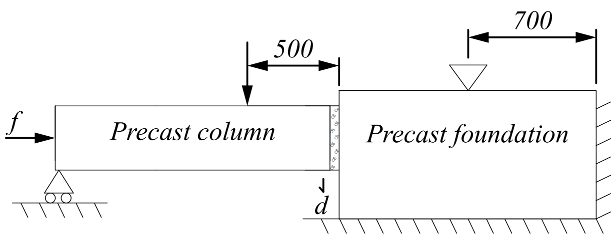

Figure 11. Schematic presentation of the bending tests.

Table 2. *Key parameters in bending tests.*

Test number	Horizontal load F [kN]	Release agent	Grout f_{cube} [MPa]	Column f_{cube} [MPa]	Foundation f_{cube} [MPa]
01-0	0	-	61.9	72.8	71.0
01-50	50	-	61.9		
01-100	100	-	61.5		
02-0	0	Thin plates	61.5	69.1	65.4
02-50	50	Thin plates	60.9	72.8	71.0
02-100	100	Thin plates	60.9	69.1	65.4

Part of the load P was transferred to the other end of the column, so the amount of shear through the bolted connections had to be calculated. In the shear tests, the transverse load was applied with minimized lever arm, which means that transverse load $P \approx$ Shear force through the connection. Measured shear force-displacement relationships are presented in *Figure 12*. Connections without a release agent showed stiffer performance than connections, where two thin plates were assembled within the joints.

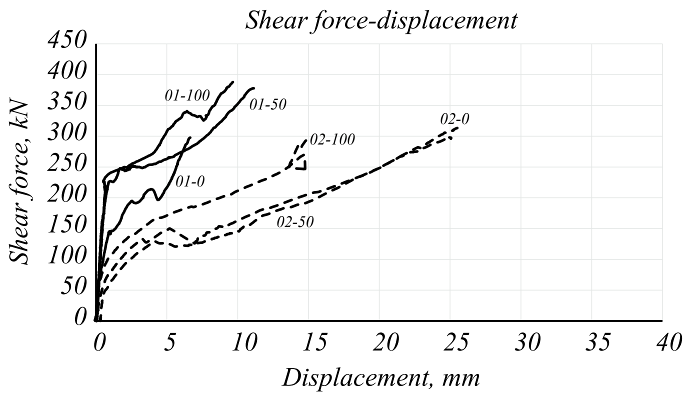

Figure 12. Shear force-displacement relationships.

SHEAR TESTS OF THRELDA® ANCHOR PLATES

THRELDA® Anchor plates 150×150-220/16 and 300×300-220/30 [8] were cast inside concrete elements and loaded by shear force and combination of shear and tensile force through customized steel plates (see *Figure 13*). Those customised plates were equipped with welded couplers to apply the external loads. Bolts 8.8 were used to attach the steel plate to THRELDA® Anchor plates. The plates were affixed flush to THRELDA® Anchor plates and no grouted layer existed between the two attached elements.

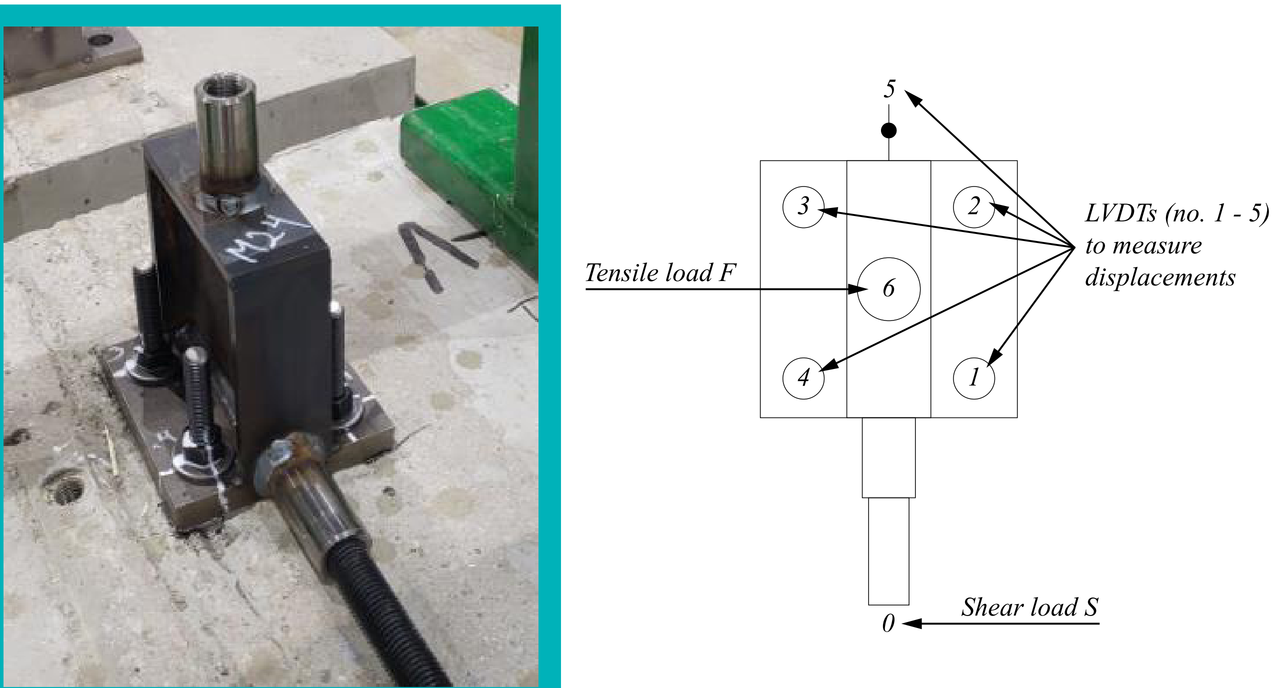

Figure 13. Test arrangement. Re-printed from EUFI29-22002233-T1.

The tests were conducted to measure the shear force associated with a slip between the steel plate and THRELDA® Anchor plate. Bolt holes had designed clearance of a precast column connection (+/- 5 mm) to ensure that there is no direct contact between the threads and the steel plate. The tests involved varying test parameters such as the size of the THRELDA® Anchor plate, torque applied to the bolts, and maintaining a constant external tensile load throughout the process (refer to *Table 3*).The applied torques are based on recommended minimum and maximum values defined for anchor bolts in Peikko's technical manual, to ensure snug-tight but avoid yielding [7].

Table 3. Varied parameters in the shear force tests.

Test number	THRELDA® type	Axial tension F [kN]	Torque T [Nm]
1.1	150×150	0	120
1.2	150×150	0	120
1.3	150×150	0	120
2.1	150×150	0	170
2.2	150×150	0	170
2.3	150×150	0	170
3.1	150×150	0	150
3.2	150×150	100	150
3.3	150×150	100	150
4.1	300×300	0	250
4.2	300×300	0	250
4.3	300×300	0	250
5.1	300×300	0	1150
5.2	300×300	0	1150
5.3	300×300	0	1150
6.1	300×300	500	700

Load-displacement relationships were produced from the measured data and the pattern from test 1.1 is presented in *Figure 14* as an example. While LVDTs 1 – 4 were measuring the slip between the beam and bolts, LVDT 5 was measuring the overall displacement of the steel plate in direction of load. All shear tests were stopped before the failure of the anchor bolts, but after the slip of the bolted assembly.

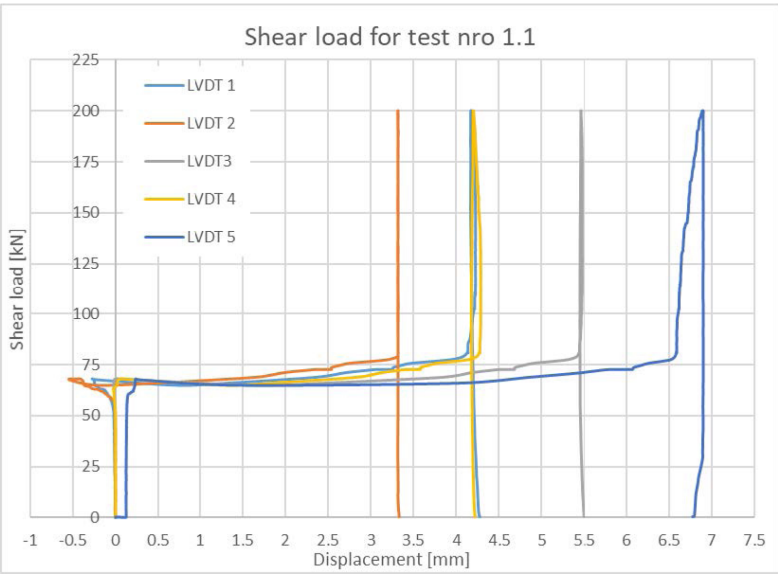

Figure 14. Measured data from test 1.1. Re-printed from EUFI29-22002233-T1, Appendix 1.

EVALUATION OF THE TEST RESULTS

Shear and bending tests of column connections

In the shear tests for bolted precast column connections, all four connections behaved fairly similarly and linearly until the load level of ~ 40 kN was reached. After that, the stiffness of the connections started to decrease as shown in *Figure 15*. The stiffness decrease was associated with the cracking of grout (see *Figure 15*).

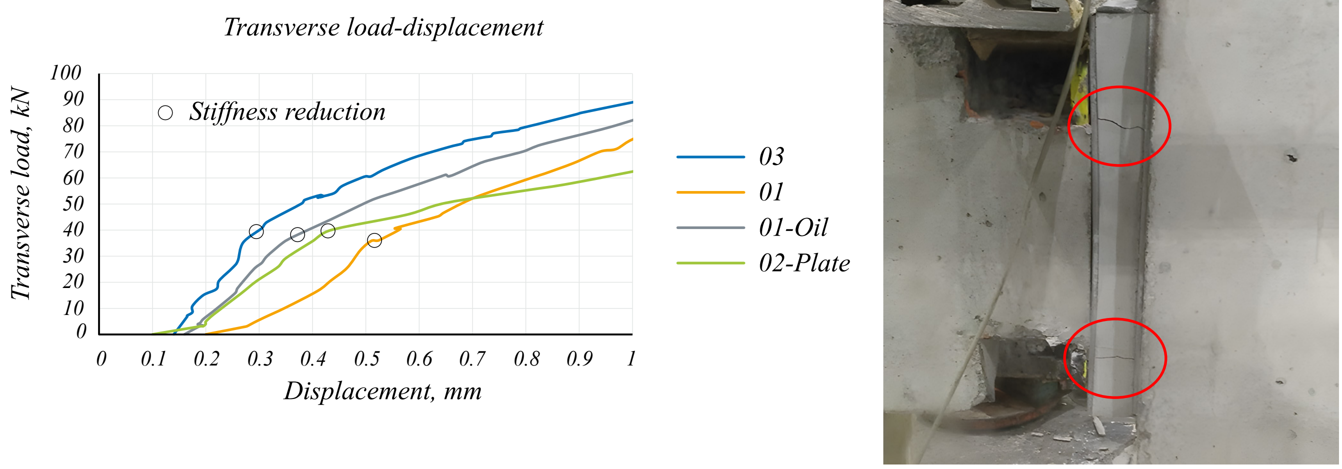

Figure 15. The first observed stiffness reductions (left) and cracks in grout (right).

In the bending tests, compressive forces were also transferred through the joint because of horizontal force F and the lever arm of transverse load P. However, in the joints with thin steel plates at the concrete-grout interface, the shear force-displacement patterns are almost equal with the patterns from shear tests without transverse compressive forces. This indicates that using thin plates as a release agent negates the friction effects by significantly reducing the coefficient of friction. When the joints are not treated by release agent (tests 01-0, 01-50 and 01-100), the compressive forces maintain friction effects, which significantly enhances the stiffness of the joint and delays the start of inelastic behaviour (assumably cracking of grout).

Shear tests of THRELDA® Anchor plates

The measured slip loads (load associated with the major slip) are presented for each test in *Table 4*.

Table 4. Measured slip loads.

Test number	Slip load S [kN]	Slip load, average [kN]	Characteristic value [kN]
1.1	67		
1.2	61	66	49.4
1.3	71		
2.1	86		
2.2	100	93	69.7
2.3	94		
3.1	75	75	
3.2	50	58	
3.3	65		
4.1	112		
4.2	100	116	55.7
4.3	135		
5.1	361		
5.2	318	365	198.0
5.3	417		
6.2	208	**195**	
6.3	182		

Average slip loads from *Table 4* are then used as data points for drafting the relationship between the slip force and torque to tighten the nuts (see *Figure 16*).

The blue curve shows data from tests without external tensile force and the orange curve shows data from tests with constant tensile force F. While the amount of torque has fairly linear effect on slip force, the presence of external tensile force tends to reduce the force needed for major slip. This is reasonable, because applied tensile force is increasing the tensile stress of bolts. The patterns should be considered only as directive, and they are usable only for assessing the performance of tested configurations.

It should be also noted that the effect of torque (preload of bolt) is highly dependable on the conditions of the thread contact between the nut and the bolt [9]. If the threads are rusted or unclean, there is more friction and bigger torque may be needed for ensuring a snug-tight position. Vice versa, if the threads are lubricated, friction effects are reduced. In the tests, the threads of the bolts were lightly lubricated before tightening.

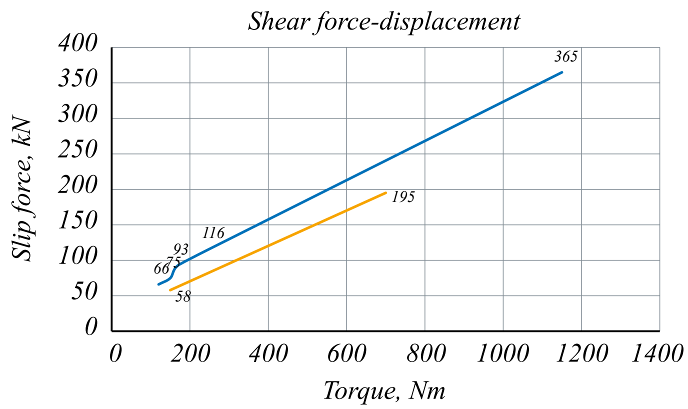

Figure 16. Slip force S – Torque relationship from THRELDA® Anchor plate tests.

The calculated maximum shear forces in the serviceability limit states

Based on the test results, the maximum shear force in the serviceability limit states is associated with the force causing the cracking of grouted joints (column connections) or the slip force (THRELDA® connections). Next, these maximum shear forces are confronted against the calculated maximum shear forces. Calculated values are based on the design shear resistances from the technical manuals of HPKM® Column shoes and THRELDA® Anchor plates [5], [8].

The design resistances are converted into the characteristic loads by considering the load factor of 1.4, which is considered as an intermediate value of the load factors 1.35 for dead loads and 1.5 for variable loads. The characteristic loads are usually given in structural plans for designing the structures and their connections. For static ULS design, these loads must be combined and multiplied with appropriate load factors. For static SLS design, these loads are combined, but used without load factors. Since this paper is dealing with the requirements of the serviceability limit states, the unfactored characteristic loads are here considered as the calculated maximum shear forces.

When calculating the design shear resistance of the column connection, only bolts in one row are considered in accordance with the methods adopted by EOTA [10].

Table 5. Calculated maximum shear forces.

Connection type	The design shear resistance acc. to Peikko's TMA [kN]	The maximum characteristic shear load [kN]
HPKM 16	40	28.6
THRELDA® 150×150	67	47.9
THRELDA® 300×300	265	189.3

In general, the calculated maximum shear forces are safe and conservative for design of such assemblies in the serviceability limit states. The only exception is THRELDA® Anchor plates 300 × 300 with minimum torque since the average slip load 116 kN was observed. In that case, if the slip cannot be accepted, it is recommended to use the maximum torque recommended by Peikko.

CONCLUSIONS

This white paper summarizes tests that show how bolted assemblies of precast concrete structures can transfer shear loads in both grouted joints and flush steel-to-concrete and steel-to-steel joints, and how transverse tensile or compressive loads affect their performance.

The use of oversized bolt holes in these systems results in inelastic behaviour at significantly lower load levels than the ultimate load of the assembly. Nevertheless, Peikko's recommended design methods ensure a safe and conservative design of such connections.

To further improve the structural behaviour of bolted connections with oversized bolt holes, slip in the system can be eliminated. Especial care must be taken with joints loaded by cyclic shear or significant shear forces with intolerance for slipping. Peikko is currently developing different options for creating slip-resistant bolted connections, which will be presented in a future white paper.

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