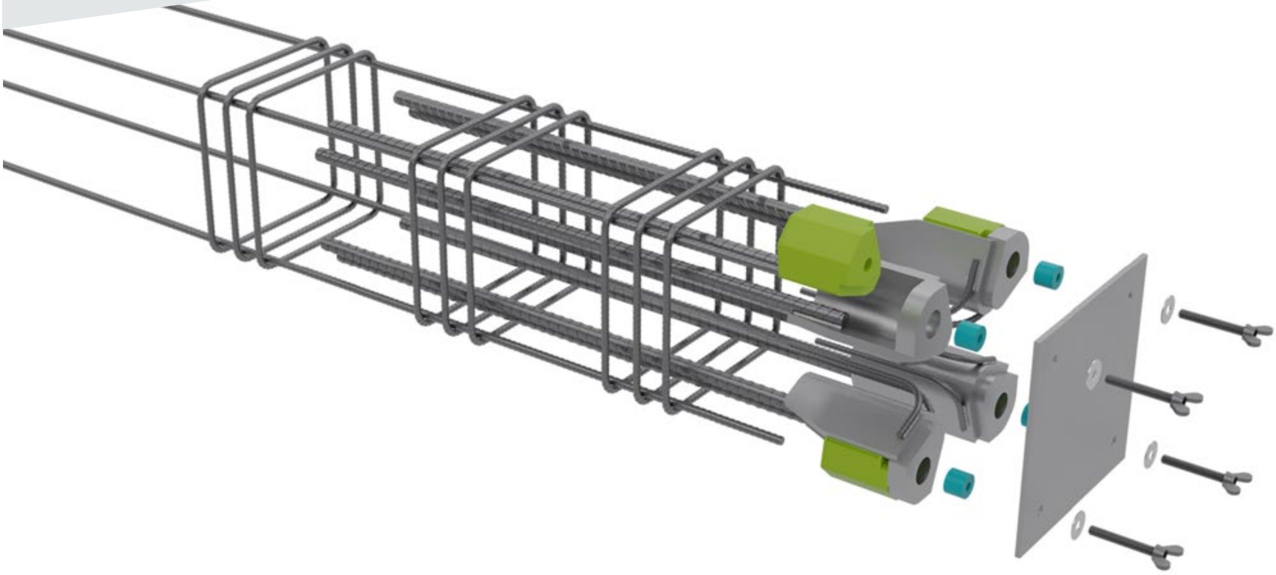
PEIKKO
WHITE PAPER



NEW GENERATION OF COLUMN SHOE CONNECTIONS

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INTRODUCTION

BOLDA® Column Shoes are fastening components used to create cost-effective stiff connections between precast concrete columns and foundations or between precast columns and other columns. Precast concrete columns show many competitive advantages, including speed of construction, smallest tolerances, high fire resistance, and high quality. Connections between precast columns are quick and easy to install, while also being economical. Peikko Group aims to make the design process quicker and easier. ETA's based on common understanding within the test procedures simplify designers' work, because the same design rules and methods, essentially a common design language, are valid and can be used all over Europe, and they are also widely accepted outside of Europe.

The development of the column shoe connections started at Peikko already in the early '80s. Since then, more than 50 large scale tests have been carried out in accordance with the respective up-to-date guidelines.

Below, the development and improvement of Peikko column shoe connections and the evaluation of various experimental and theoretical investigations are presented in detail.

CE MARKING

In 2013, the Construction Products Regulation (CPR) replaced the Construction Products Directive (CPD). The CPR is directly applicable in all member states, whereas the CPD had to be implemented through national legislation.

The European Technical Approvals (ETApp) issued until June 2013 remain valid until the end of their validity period and in some cases also contain supplementary regulations for design. These "old" ETApp will be replaced by 2018 with a new type ETA, the European Technical Assessment (ETAss). According to the Construction Products Regulation, the new European Technical Assessments – in contrast to the European Technical Approvals – no longer have a validity period. It should be noted that the European Technical Assessments ETAs may no longer contain design provisions.

The new ETAss are issued based on European Assessment Documents (EAD). Existing Guidelines for European Technical Approval (ETAG) can be used as EAD on a transitional basis. The documents of a "Common Understanding of Assessment Procedure" (CUAP) must be transferred to an EAD if a European Technical Assessment is to be issued in future based on these documents.

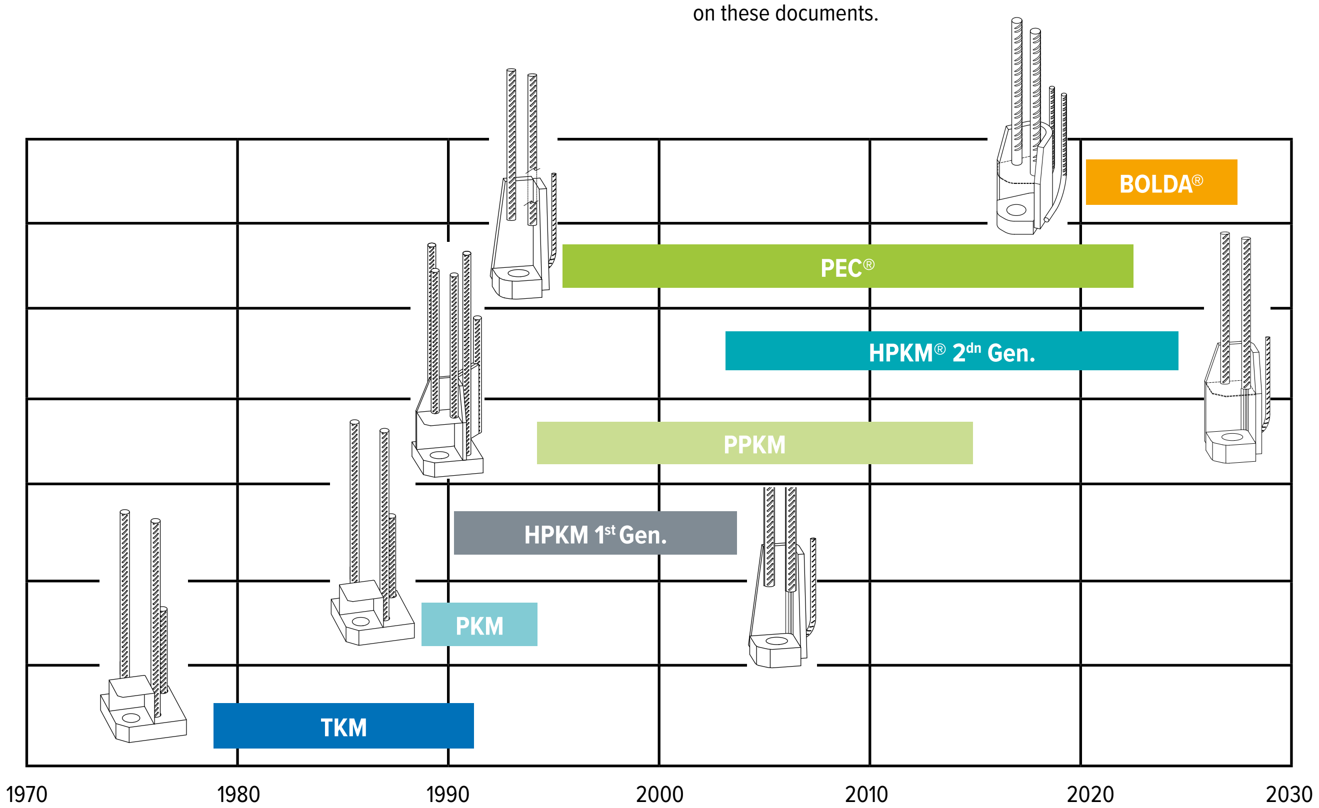


FIGURE 1: CHRONOLOGICAL DEVELOPMENT OF PEIKKO COLUMN SHOE SYSTEMS

A European Technical Assessment is issued by a Technical Assessment Body (TAB). The European TABs are organized in the European Organization for Technical Assessment (EOTA).

Based on an ETA, a certificate of constancy of performance and a declaration of performance (DoP) of the manufacturer, a CE marking may be affixed to the products. In the current phase of change, national approvals, European Technical Approvals (ETA "old"), and European Technical Assessments (ETA "new") are available for various product groups. CE marking is therefore a declaration that the product meets certain safety requirements such as mechanical and/or fire resistances. The application for a European Technical Assessment of EOTA (ETA) and the associated CE marking is voluntary. The ETA contains all required characteristic values, which have been obtained and verified according to the recognized rules of technology. It is the unique opportunity to describe the performance characteristics of column shoe systems.

Peikko's approach is much more comprehensive – not only the safety-relevant properties of a product are in focus, but also the corresponding technical rules and dimensioning regulations are constantly improved and further developed with the aim of providing faster and more efficient system solutions for the user. This supports further development of reinforced concrete construction in the long run.

BOLDA® COLUMN SHOES

GEOMETRY

BOLDA® column shoe connections are used to create cost-effective moment resisting stiff connections between precast concrete columns and foundations, or between precast concrete columns.

The system consists of column shoes and corresponding anchor bolts. Column shoes are cast into precast a concrete column, whereas anchor bolts are cast into foundation or another column. On construction site, the columns are erected on the anchor bolts, adjusted on the correct level and vertical position, and fixed to the bolts. Finally, the joint between column and base structure is grouted (Figure 2).

The BOLDA® column shoe (see Figure 3) consists of a horizontal base plate, vertically arranged side plate, vertical main anchorage bars and bent rear bars. Additional non-structural steel sheets, which serve as moulds when concreting the column, may be present. The components of the column shoe are connected to each other by welding.

The main dimensions of the different sizes of BOLDA® column shoes are given in Figure 4.

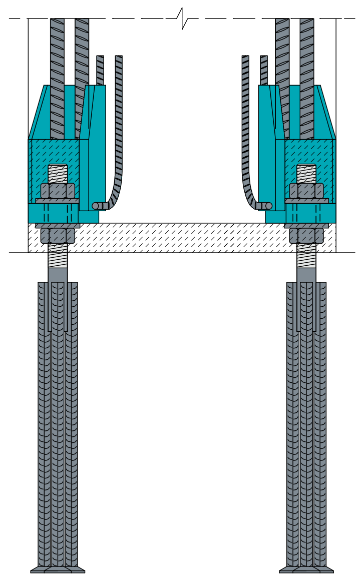


FIGURE 2: EXAMPLE FOR AN APPLICATION WITH BOLDA® COLUMN SHOE

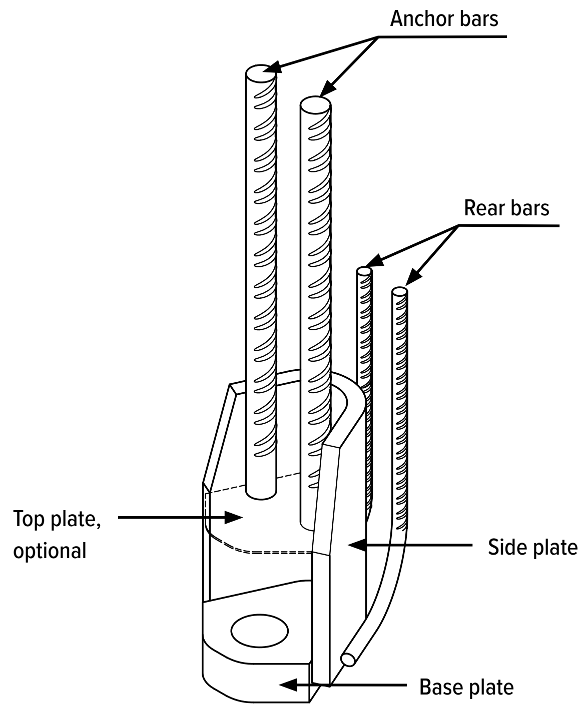
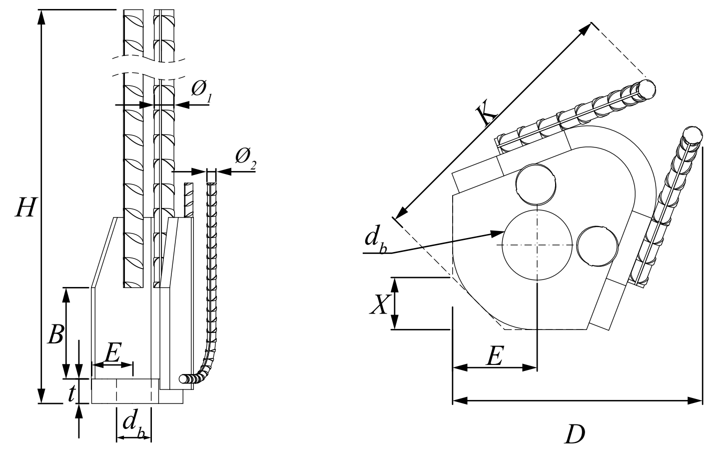


FIGURE 3: BOLDA® COLUMN SHOE



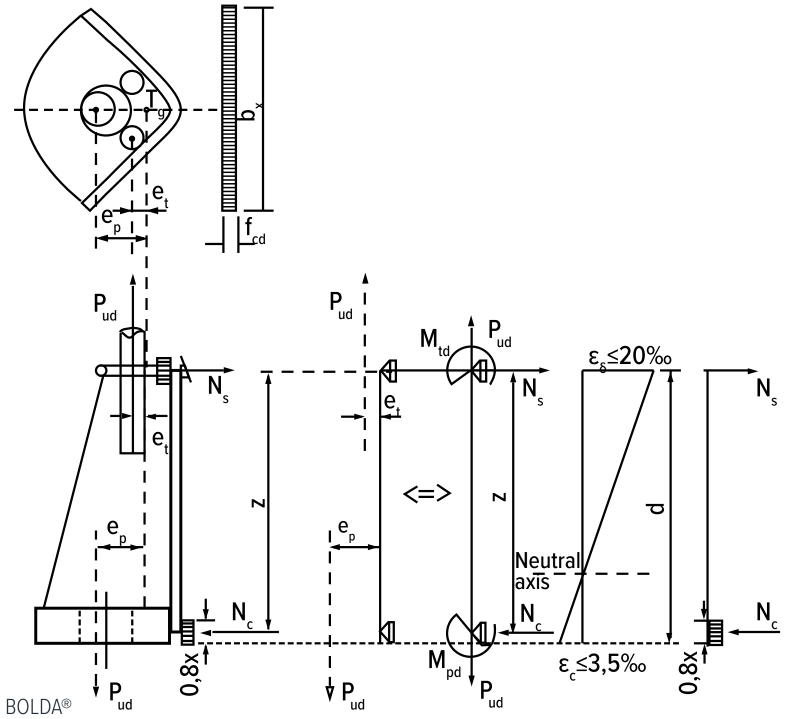
	BOLDA® 30	BOLDA® 36	BOLDA® 39	BOLDA® 45	BOLDA® 52
H	1058	1365	1600	1852	2190
t	30	35	40	50	55
B	100	130	130	140	170
E	50	60	60	60	70
d_b	40	50	55	60	70
$Ø_1$	25	28	28	32	40
$Ø_2$	10	12	14	16	16
X	30	37	37	37	42
D	153	178	195	217	245
K	173	200	220	250	269
Weight	13.7	22.6	29.4	42.5	74.9

FIGURE 4: DIMENSIONS [MM] AND WEIGHTS [KG] OF BOLDA® COLUMN SHOES

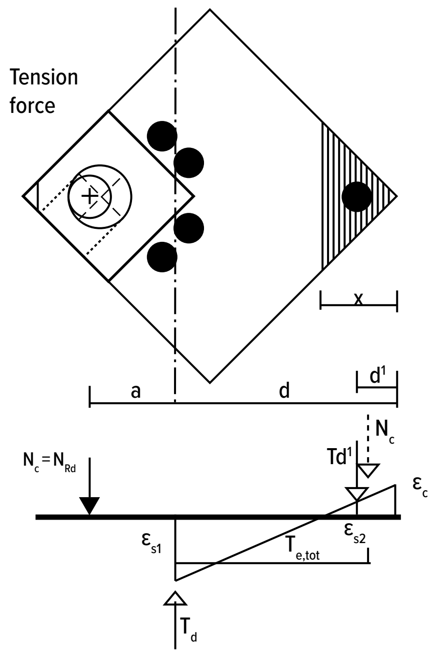
LOAD TRANSFER MECHANISM

Column-to-column or column-to-foundation connections are usually loaded by axial normal forces and horizontal shear forces in combination with bending moments. The bending moments may be separated in pairs of tension and compression forces. The shear forces are transferred from one concrete element to the other via the cross section of the bolt. Additional friction forces may be generated if compressive forces are present. The tension forces in the baseplate are transferred by the anchor bolts to the base structure. Due to axial shift between the through-hole in the baseplate (= axis of the anchor bolt) and the axis of the anchor bars of the column shoe, an eccentricity appears. This eccentricity is compensated for by a pair of horizontal pair of forces (see Figure 5 a). In case of tension loads in the anchor, the moment due to eccentricity is taken over by a tension force in horizontally arrange stirrups and the compression force acting on the side plate. By contrast, the compression forces in the anchor bolts lead to the compression forces on the upper part of the side plate, and the tension forces in the horizontal part of the rear bars.

With the older versions of column shoes TKM and PKM, the eccentricity of the force within the anchor bolt was compensated with a vertical pair of forces consisting of the connecting reinforcement of the column and the vertical hanger reinforcement welded to the column shoe (see Figure 5 b).

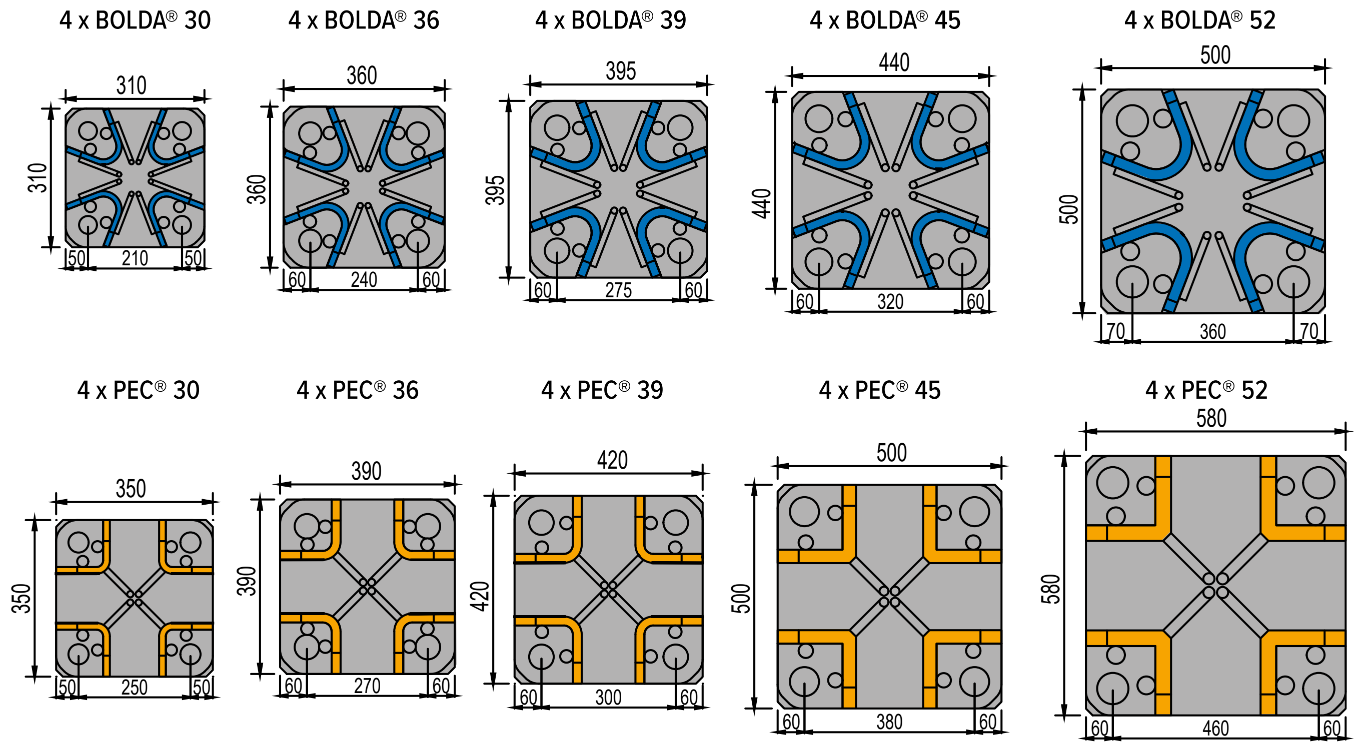


A) BOLDA®

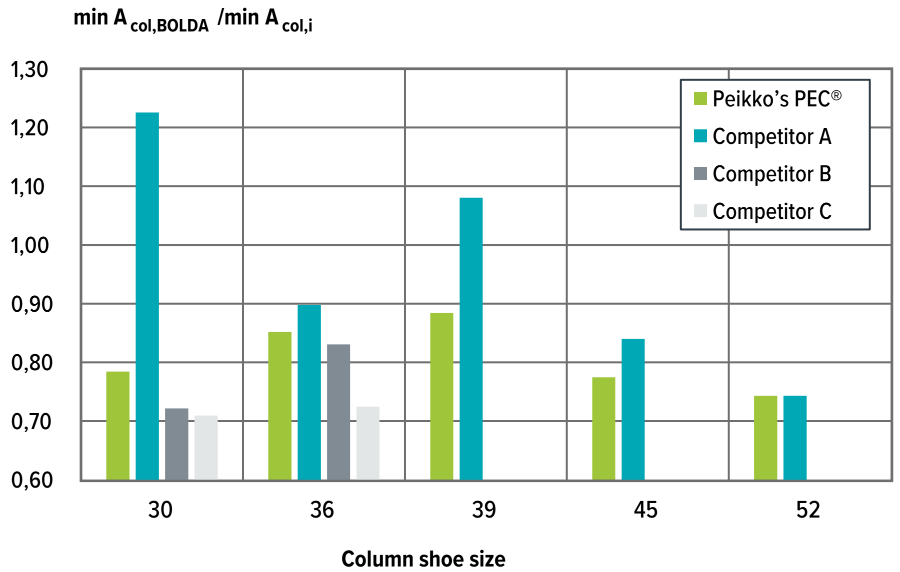


B) TKM/PKM

FIGURE 5: LOAD TRANSFER MECHANISM OF DIFFERENT COLUMN SHOE SYSTEMS FOR TENSION FORCES WITHIN THE ANCHOR BOLTS



A) GEOMETRY OF COLUMN CROSS SECTIONS FOR BOLDA® AND PEC® COLUMN SHOES



B) COMPARISON

FIGURE 6: MINIMUM REQUIRED COLUMN CROSS SECTIONS OF BOLDA® COLUMN SHOES COMPARED TO PEC® COLUMN SHOES AND TO VARIOUS COMPETITORS

CONSTRUCTIONAL IMPROVEMENTS

Further changes to improve the overall stiffness of the column shoes have been made. Already during the development process of HPKM® column shoes we realized that building a straight form of the side plate up to the starting point of the anchor bars increases the stiffness of the connection. With BOLDA®, the outer edges of the base plate as well as the side plates are only inclined at 48° to each other instead of the 90° for previous systems TKM or PKM, which in turn leads to increased stiffness. This reduced angle in combination with the different positioning of the rear bars results in a significant reduced space requirement for each column shoe, which consequently leads to 12% to 26% smaller column cross sections compared to predecessor type (compare Figure 6).

During the development process, efforts were also made to further improve and streamline the production process. This was achieved, for example, by optimizing the number of welding seams, which subsequently improves indirectly the overall safety due to minimization of error-proneness.

Due to the above-mentioned improvements, the overall form of the BOLDA® column shoes is more compact and stiffer compared to older versions. BOLDA® column shoe enables 20% slimmer cross-sections compared to PEC®.

In combination with the optimization of the production process, a significant reduction in the overall CO_2 footprint was achieved.

INVESTIGATIONS
EXPERIMENTAL

General
There is no one-to-one correspondence between the mechanical resistance of a column shoe as delivered and the mechanical resistance of a column shoe connection. A connection is subjected to various action effects like axial force, shear force, and bending moment in different combinations, and the stiffness of the connection also has an impact on the behavior and the design of the column. It is impossible to determine the mechanical resistance or stiffness of a column shoe connection as a set of values determined according to different standards and guidelines. Therefore, these properties must be determined experimentally.

The EAD [1] summarizes the required tests and the related test setup, and gives guidance on the evaluation of the test results. The values determined in this way can then be used with the design method specified in TR 068 [2].

The following tests are mandatory according to EAD:
- a) Bending Resistance Tests
- b) Bending Stiffness Tests
- c) Shear Resistance Tests
- d) Fire Resistance investigations

a) Bending Resistance (BR) Tests
The target of the Bending Resistance (BR) tests is to show that the resistance of the BOLDA® column shoe connection is at least equal to the bending resistance of a monolithic cast-in-situ column.

b) Bending Stiffness (BS) Tests
In general, design of column-to-column or column-to-foundation connections with column shoes should follow the design principles given in EN 1992-1-1 for monolithic columns with continuous reinforcement. The stiffness of columns and the moment-deflection-behavior respectively is considered in EN 1992-1-1 by different buckling factors or buckling lengths. Therefore, within these tests it is verified whether for column shoe connections the same assumptions as for cast-in-situ columns apply. With column shoe connections (column A in Figure 7), different zones along the column length compared to cast-in-situ columns (column B in Figure 7) must be considered. Within **Zone 1,** columns with column shoe connections do not differ from cast-in-situ columns since the existing reinforcement is identical. In **Zone 2**, the flexural stiffness of column A with column shoes is much higher compared to column B. This is caused by the overlapping of the anchor rebars of the column shoe with the existing reinforcement of the column. In contrary, column B is designed with continuous reinforcement in **Zone 2** according to EN 1992-1-1 [4], even though in practice spliced reinforcement would be more common.

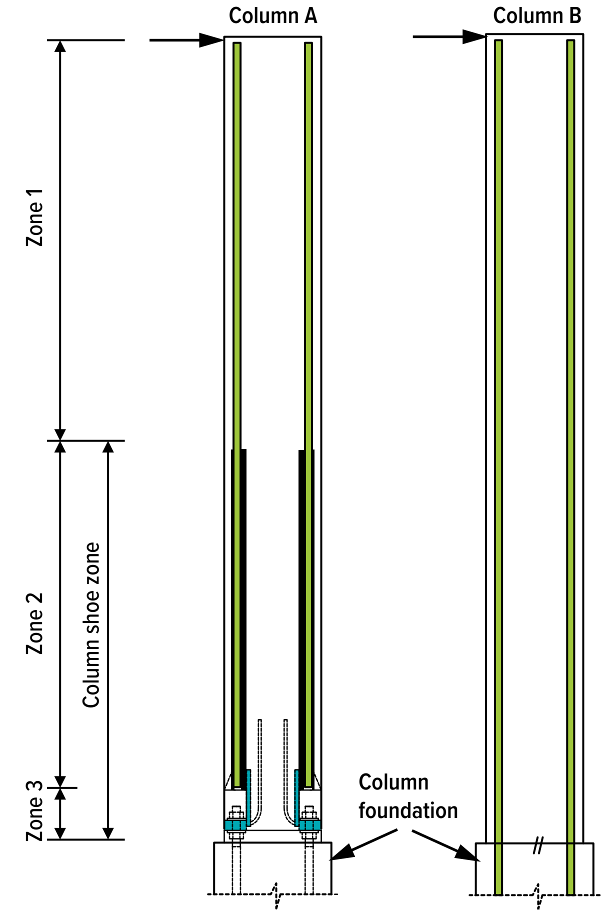


FIGURE 7: DIFFERENT STIFFNESS ZONES OF CANTILEVER COLUMNS

In **Zone 3**, the flexural stiffness of column A is lower compared to column B, mostly due to the reduced effective concrete section at the bottom of the column. Further reduction of the stiffness is caused by the eccentric tension forces in the column shoes (compare Figure 7). The schematic location of the measuring points along the length of the column is shown in Figure 8.

With cantilevered columns, the stiffness of the column shoe connection plays the most important role compared to other statical systems. The behavior of cantilevered columns is extremely sensitive to geometrical nonlinearity and therefore considerably influenced by the stiffness. Any negative effect caused by a flexible connection will be amplified within such system.

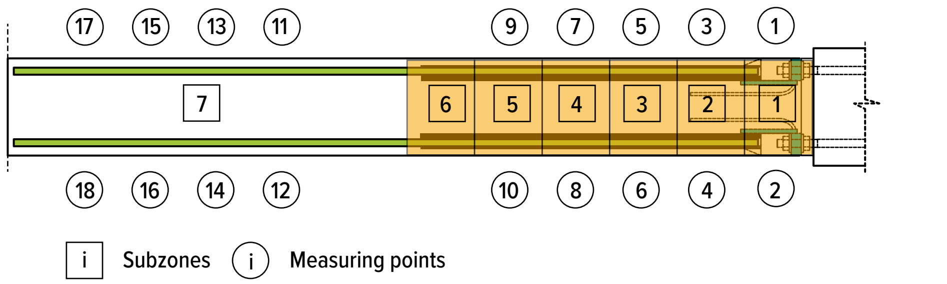
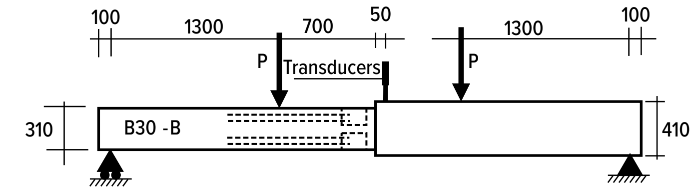


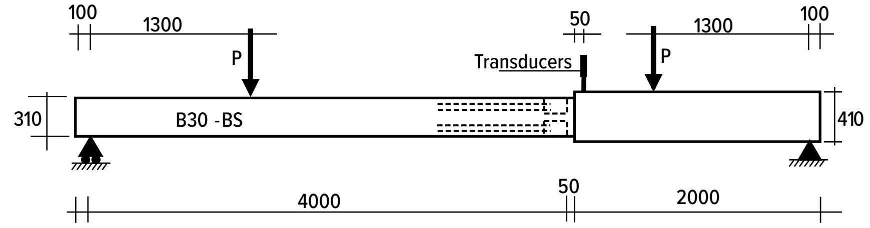
FIGURE 8: LOCATION AND NUMBERING OF THE SUBZONES AND MEASURING POINTS (TRANSDUCERS), SCHEMATIC

c) Shear resistance tests
In the shear tests, it is assumed that the maximum shear forces are caused by a horizontal load at a certain distance from the foundation level (e.g. vehicle impact). The maximum shear resistances obtained in the tests are compared to the theoretical values of two acting columns shoes. The theoretical resistances are determined according to EN 1993-1-8 considering both the base plate and the bolt.

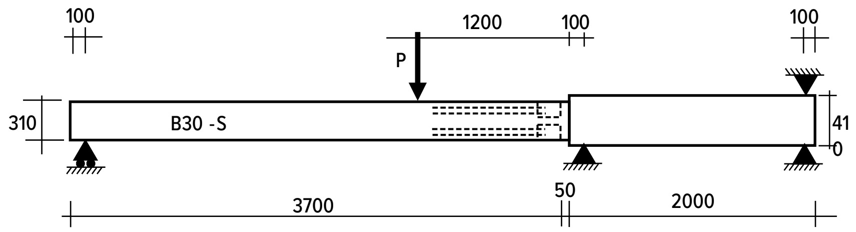
The different test setups for all three tests are shown in Figure 9.



A) BENDING RESISTANCE TEST ARRANGEMENT



B) BENDING STIFFNESS TEST ARRANGEMENT



C) SHEAR TEST ARRANGEMENT

FIGURE 9: EXAMPLES OF TEST SETUP ACCORDING TO EAD [1]

EVALUATION OF TEST RESULTS
BENDING RESISTANCE
The observed bending resistance moment M_{obs} and the related failure modes of the column shoe connections are summarized in Table 1. In the two tests, compression failure of the concrete and/or grout was observed. This means that the ultimate capacity of the column shoe was not reached, and the bending resistance moment is higher than the value given in Table 1. For this reason, these two tests will be disregarded in the further evaluation.

The theoretical bending resistance M_t has been calculated acc. to EN 1992-1-1 considering the measured material properties for compressive strength of the concrete and the grout, yield strength of the rebars, as well as yield strength of the anchor bolts. According to EAD, the comparison of the test results with the theoretical values $m_k = (M_{obs}/(\eta_{d0} \cdot M_t))$ contains a bending resistance factor $\eta_{d0} \leq 1.0$ used for the design of the test specimen. This value was taken as $\eta_{d0} = 1.0$.

The evaluation shown above clearly confirms that the load bearing behavior of the column with BOLDA® column shoe connection is equal compared to the behavior of a monolithic column.

Test	f_{gr}	b = d	d_1	$f_{bolt,y}$	A_{sp}	M_t	$\eta_{d,0}$	M_{obs}	$M_{obs}/(\eta_{d,0} \cdot M_t)$	Failure mode
	MPa	mm	mm	MPa	mm²	kNm	-	kNm	-	
B30-BS.2 [1]	53.2	310	50	803	561	209.8	1.00	215.7	1.03	Bolt
B30-B [1]	49.9	310	50	803	561	208.5	1.00	220.2	1.06	Bolt
B30-BS.2 [2]	48.2	380	50	918	561	311.3	1.00	330.2	1.07	Bolt
B39-B [1]	49.2	390	60	855	976	485.3	1.00	453.8	-	concrete compression
B39-B [2]	48.2	420	60	894	804	486.5	1.00	497.3	1.03	Bolt/column shoe
B52-B [1]	49.9	500	70	964	1758	1273.4	1.00	1084.9	-	concrete compression
B52-B [2]	40.9	580	70	890	1479	1214.6	1.00	1343.8	1.11	Bolt/column shoe
B52-BS.2 [2]	43.5	580	70	890	1479	1218.9	1.00	1322.3	1.09	Bolt/column shoe
Mean value m_m									1.07	
Standard deviation s_m									0.032	
Characteristic value (unknown standard deviation) $m_k = m_m - k_n \cdot s$ Statistical factor acc. EN 1990: k_n = 2,18									1,00	

TABLE 1: EVALUATION OF THE BENDING RESISTANCE TESTS, RESULTS FROM [9, 10]

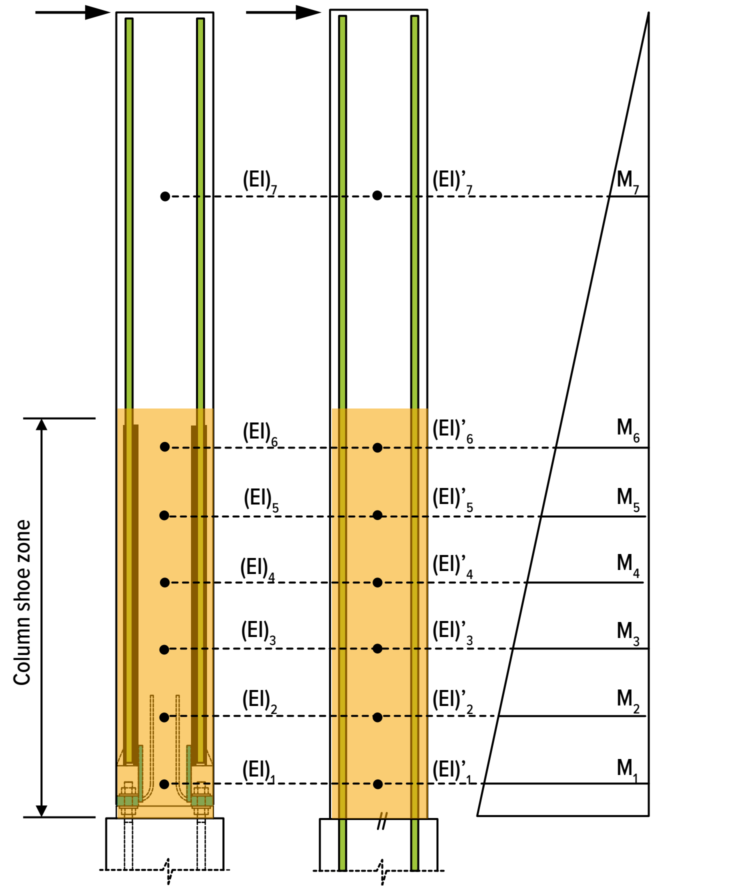
BENDING STIFFNESS

Two bending stiffness tests have been carried out using BOLDA® 30 and BOLDA® 52. The strains on the top and the bottom along the column axis have been determined by means of the measured differential displacement as given in Figure 9 b) and Figure 8. The bending stiffness of the column shoe connection is evaluated comparing the residual deflections determined in the tests with column shoe connections and monolithic columns see Figure 10). The subzones in Figure 10 are identical to the one shown in Figure 7 and Figure 8.

The bending moment in each subzone and the related stiffnesses in the middle of each subzone as well as the maximum bending moment at the bottom of the column are summarized in Table 2. The location of the subzones is as follows (compare Figure 7 and Figure 8):

- Subzone 1 is identical to Zone 3 = column shoe connection zone
- Subzones 2–5 are in the column shoe zone (Zone 2), whereas subzone 6 is located in the mixed zone at the end of the column shoe. The stiffness for subzone 6 is calculated using the mean value of measured deformations within subzone 5 and subzone 7.
- Subzone 7 is outside of the column shoe zone (= Zone 1). In this area, the reinforcement layouts of column A and B are identical and lead to equal stiffnesses. The stiffness for this subzone is calculated using the mean value of measured deformations of measuring points 11 to 18.

The maximum deflections at the top of the column, calculated from the relative subzone stiffnesses, are additionally shown in Table 2.



A) COLUMN A WITH COLUMN SHOES

B) COLUMN B (MONOLITHIC) WITH CONTINUOUS BENDING REINFORCEMENT

C) MOMENT DISTRIBUTION ALONG COLUMN AXIS

FIGURE 10: PROCEDURE FOR STIFFNESS COMPARISON

	BOLDA® 30			BOLDA® 52		
Subzone i	M_i	Column A	Column B	M_i	Column A	Column B
		$(EI)_i$	$(EI)'_i$		$(EI)_i$	$(EI)'_i$
	kNm	[MNm²]	[MNm²]	kNm	[MNm²]	[MNm²]
7	60.5	4.69	4.69	384.7	101.36	101.36
6	123.1	9.65	6.00	784.9	131.51	114.56
5	129.1	13.14	5.90	823.9	147.17	113.32
4	136.8	13.05	5.88	871.3	162.73	112.78
3	144.6	12.22	5.71	918.6	169.71	111.62
2	152.3	9.22	5.15	966.0	190.58	109.74
1	160.1	3.24	5.03	1013.3	43.56	104.12
$1.0 \cdot M_{1,0}$	163.9			1037.0		
Deflection		v_{shoe}	v_{ref}		v_{shoe}	v_{ref}
		[mm]	[mm]		[mm]	[mm]
		164.9	190.4		261.6	249.3
v_{shoe}/v_{ref}		0.866		1.049		

TABLE 2: COMPARISON OF BENDING STIFFNESSES IN DIFFERENT SUBZONES AND CALCULATED DEFLECTIONS AT THE TOP OF THE COLUMNS, RESULTS FROM [9, 10]

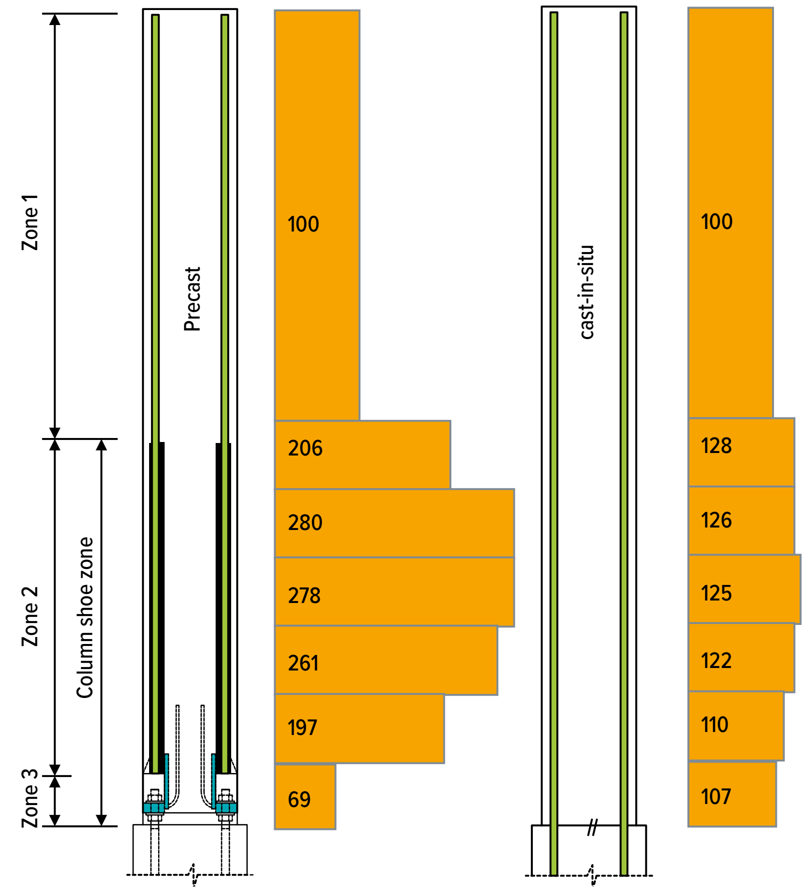


FIGURE 11: EVALUATION OF TEST RESULTS FOR COLUMNS A (BOLDA® 30) AND B – RELATIVE BENDING STIFFNESS OF SUBZONES IN %

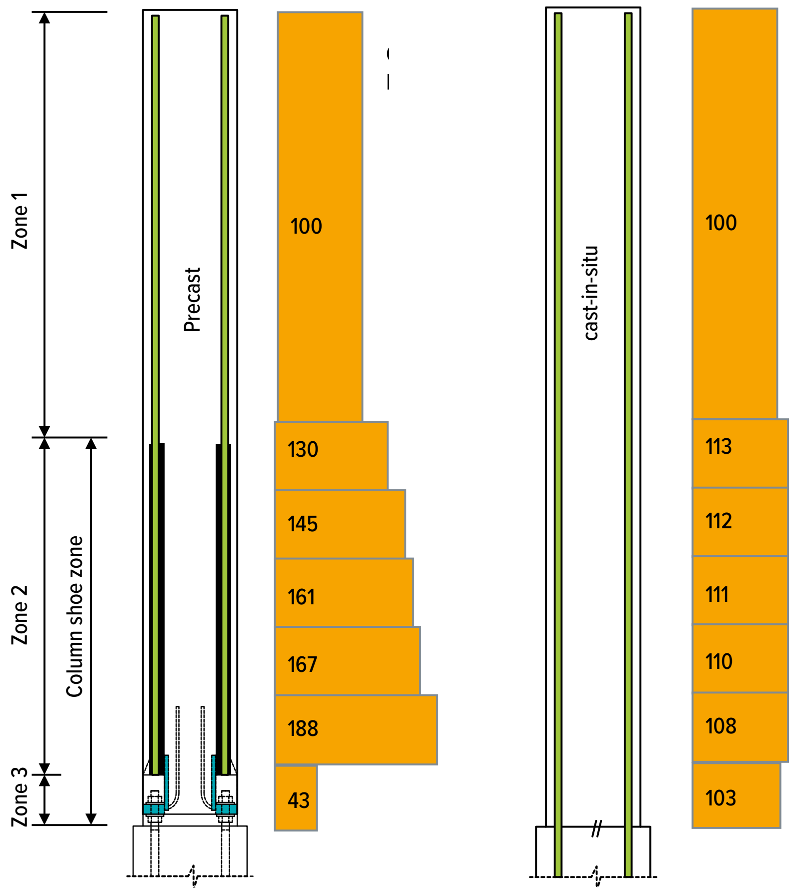


FIGURE 12: EVALUATION OF TEST RESULTS FOR COLUMNS A (BOLDA® 52) AND B – RELATIVE BENDING STIFFNESS OF SUBZONES IN %

Figure 11 and Figure 12 show the distribution of the bending stiffness along the column axis related to the bending stiffness of the undisturbed region (subzone 7). In zone 2, the stiffness of precast column A is for both sizes of BOLDA® column shoes significantly higher compared to the cast-in-situ columns. In Zone 3, the relative stiffness of precast column A is smaller than the value obtained for column B. Nevertheless, the higher stiffness of zone 2 will compensate for the lower stiffness in zone 3.

The calculated deflection at the top of the columns based on the measured deformations are v_{shoe} = 165 mm (BOLDA® 30) and v_{shoe} = 262 mm (BOLDA® 52). These values are ca. 13.4% lower (BOLDA® 30) and 4.9% higher (BOLDA® 52) than the reference values of the cast-in-situ columns. According to EAD [1], the ratio of is limited to $v_{shoe}/v_{ref} \le 1.05$. Therefore, the requirements are fulfilled and a factor $k_L = 1.0$ can be used in the design of the columns according to EN 1992-1-1 [4].

SHEAR RESISTANCE

Two shear resistance tests using BOLDA® 30 and BOLDA® 52 have been carried out. The results are given in Table 4. The measured shear resistances $V_{u,test}$ have been converted to $V_{e,i}$ taking into account the ratio of nominal to actual steel strength ($f_u/f_{u,test}$). The values obtained are compared to the theoretical value $V_{t,i}$.

Test	$V_{t,i}$	$V_{u,test}$	f_u	$f_{u,test}$	$f_u/f_{u,test}$	$V_{e,i} = (f_u/f_{u,test})\cdot V_u$	$V_{e,i}/V_{t,i}$
	kN	kN	MPa	Mpa	-	kN	-
B30-S [1]	198.6	346	800	889	0.90	311.3	1.57
B52-S [1]	561.5	1176.7	800	1059	0.76	894.3	1.59

TABLE 3: COMPARISON OF THE RESULTS OF THE SHEAR TESTS WITH THE THEORETICAL VALUES

The comparison in Table 3 clearly shows that the requirement $V_{e,i}/V_{t,i} \geq 1.0$ is clearly fulfilled. Therefore, a value $k_s = 1.0$ can be used in the shear design according to EN 1992-1-1.

In the following, all characteristic values are listed.

Column shoe			BOLDA® 30	BOLDA® 36	BOLDA® 39	BOLDA® 45	BOLDA® 52
Steel failure							
Resistance	$N_{Rd,s}$	[kN]	299	436	521	697	938
Bending resistance factor	η_d	[-]	1.0				
Bending stiffness factor	k_L	[-]	1.0				
Shear resistance factor	k_s	[-]	1.0				

Material	Properties	
Concrete	Compressive strength f_{ck}	30 MPa
	Tensile strength f_{ctk}	2.0 MPa
	Youngs modulus E	32000 MPa
Mortar	Compressive strength f_{ck}	50 MPa
	Tensile strength f_{ctk}	2.9 MPa
	Youngs modulus E	37000 MPa
PPM® bolt and nut	Yield strength f_{yk}	640 MPa
	Ultimate strength f_{uk}	800 MPa
	Youngs modulus E	200000 MPa
BOLDA® column shoe plates	Yield strength f_{yk}	355 MPa
	Ultimate strength f_{uk}	490 Mpa
	Youngs modulus E	200000 MPa
Reinforcement	Yield strength f_{yk}	500 MPa
	Ultimate strength f_{uk}	600 MPa
	Youngs modulus E	200000 MPa

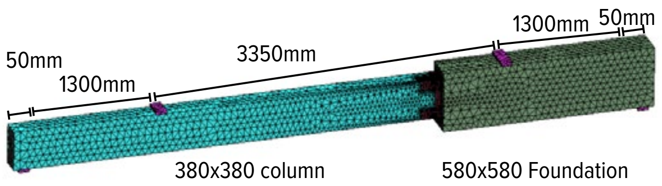
TABLE 4: MATERIAL PROPERTIES OF THE COMPONENTS WITHIN THE FE CALCULATIONS [18]

ADDITIONAL INVESTIGATIONS OF THE DEFLECTION BEHAVIOR WITH FE ANALYSIS

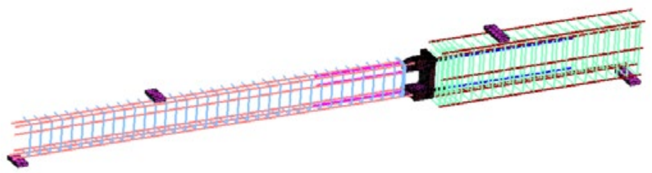
To further evaluate the load bearing behavior of column shoe connections in comparison to cast-in-situ columns, a small research project using finite element analysis of both systems has been conducted in collaboration with University of Stuttgart [18]. Two systems applying BOLDA® 30 and BOLDA® 52 column shoe connections have been investigated, as well as the associated cast-in-situ (monolithic) models. The test setup for the bending stiffness, tests acc. to Figure 9 b) including the measuring points according to the previous section have been adopted for both column shoe connections as well as monolithic cast-in-situ systems. Within the analysis, the following material properties for the different components have been used (Table 4).

The non-linear finite element program ATENA® can simulate the real structural behavior including concrete cracking, crushing and reinforcement yielding. The software has been extensively validated on experimental data and international round robin prediction analysis.

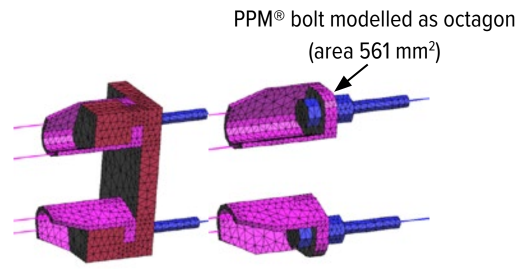
Within the FE-model, the concrete (foundation, column and mortar) and steel (shoe plates, bolts and nuts, loading/support plates) were modelled as solid elements, whereas the reinforcement (longitudinal bars and transverse stirrups, anchor bars) are modelled as 1D-beam elements with axial degree of freedom. The contact areas between reinforcement and concrete, as well as the contact areas between different solid elements, are described with a bond model. Figure 13 a) shows the complete system of solid elements and Figure 13 b) shows the discretization of the longitudinal and stirrup reinforcement, and Figure 13 c) shows the details of the FE-model of the column shoes.



A) SOLID ELEMENTS OF COLUMN, FOUNDATION AND LOADING/SUPPORT PLATES



B) 1D-BAR ELEMENTS OF THE REINFORCEMENT [18]



C) FE-MODEL FOR THE COLUMN SHOE [18]

FIGURE 13: FE-MODEL OF THE COMPLETE SYSTEM (PPM® BOLT MODELLER AS OCTAGON WITH AREA = 561 SQMM)

Figure 14 show the calculated load/moment-deflection curves of the column-foundation-system with BOLDA® 30 compared to the monolithic system. The deflections are given for the loading point in the column- and foundation-area, as well as for the position of the transducer close to the joint between column and foundation (compare Figure 9 b). In Figure 15, the crack development at different load steps are shown.

In general, the deflections increase linearly with increasing loading up to ca. 85% of the ultimate load. With further loading, the deflections increase over proportional with increasing load. This is mainly caused by progressive cracking, as well as exceeding the yield strength of the reinforcement. Failure load of the connected and the monolithic system differ only slightly by ca. 2%. Within the linear area, the deflections of the monolithic system are ca. 15% larger than the calculated values of the column shoe system (compare Figure 14). This difference is significantly increasing after passing the yield load.

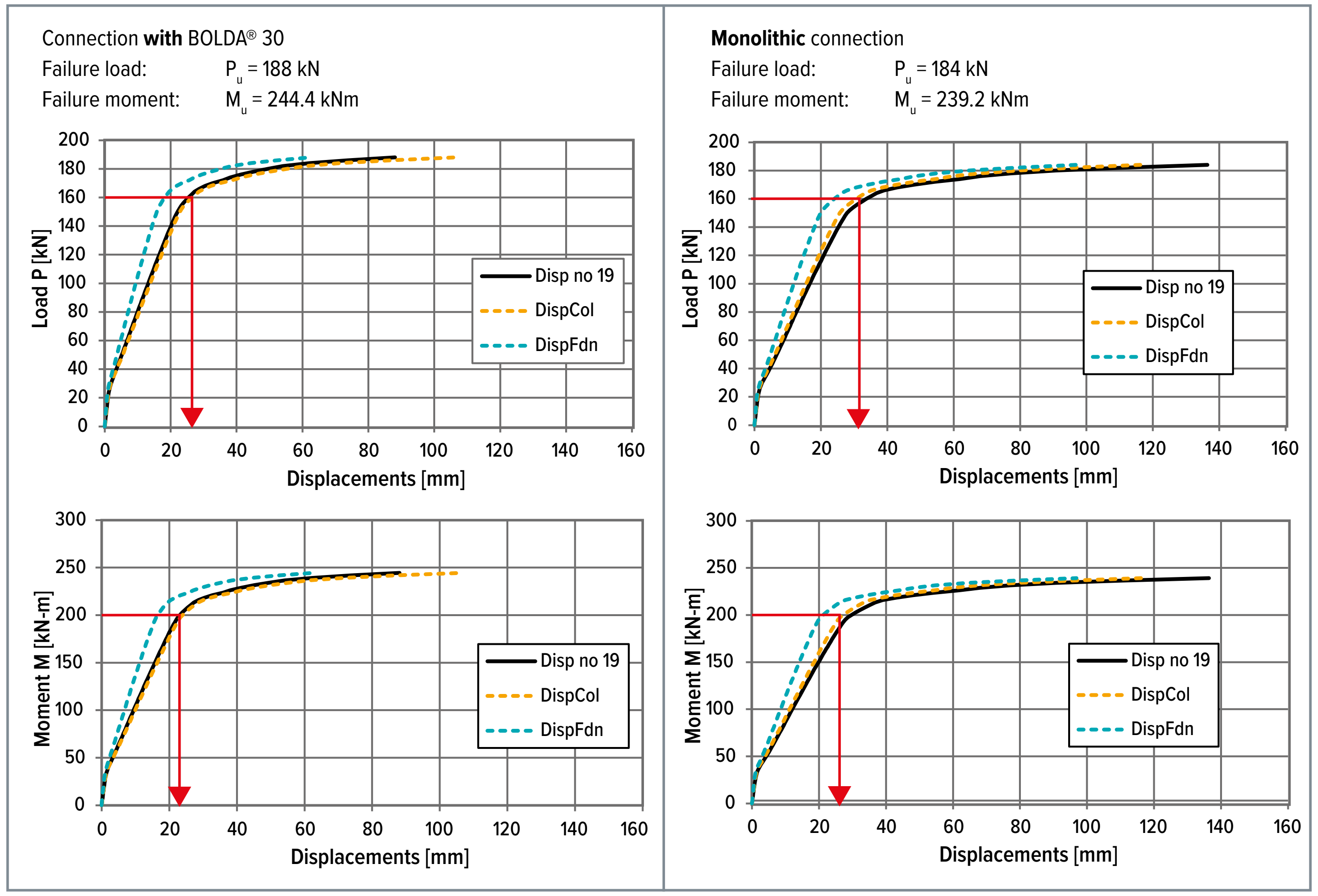


FIGURE 14: LOAD/MOMENT-DISPLACEMENT BEHAVIOR – CONNECTION WITH BOLDA® 30 COMPARED TO MONOLITHIC CONNECTION [18]

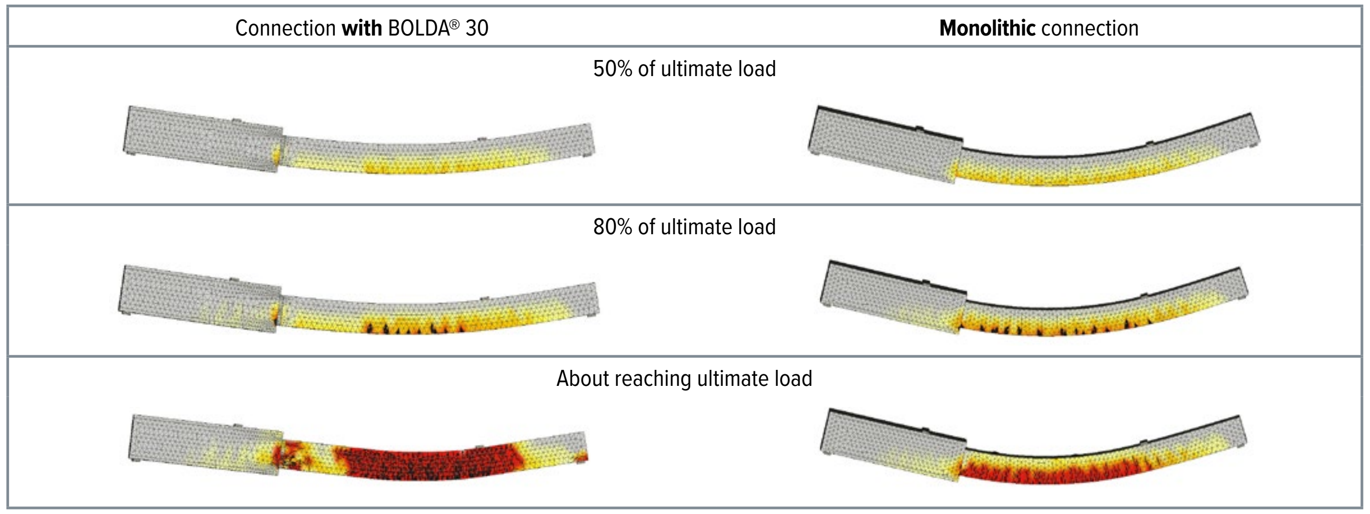
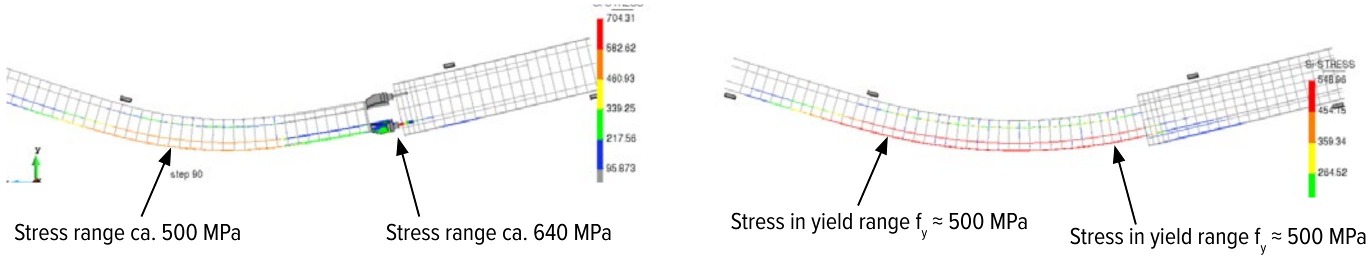


FIGURE 15: CRACK PATTERN COMPARED TO MONOLITHIC CONNECTION [18]



A) COLUMN SHOE SYSTEM

B) MONOLITHIC SYSTEM

FIGURE 16: STRESS DISTRIBUTION WITHIN THE ANCHOR BOLTS, COLUMN SHOE AND REINFORCEMENT AT FAILURE, BOLDA® 30 [18]

The ultimate stage of the column shoe system is characterized by yielding of the PPM® bolts (Figure 16 a). At this stage, the stress in the reinforcement outside of the column shoe area is in the range of σ ≤ 500 MPa. Within the monolithic system, at the ultimate failure load, the maximum stresses occur within the reinforcement in the column area between the end of foundation and the loading point (see Figure 16 b).

Figure 17 and Figure 18 show the corresponding results for the calculations using BOLDA® 52. In total, the results of the calculations confirm the above-mentioned findings and correlations regarding failure load, failure mode and deflections.

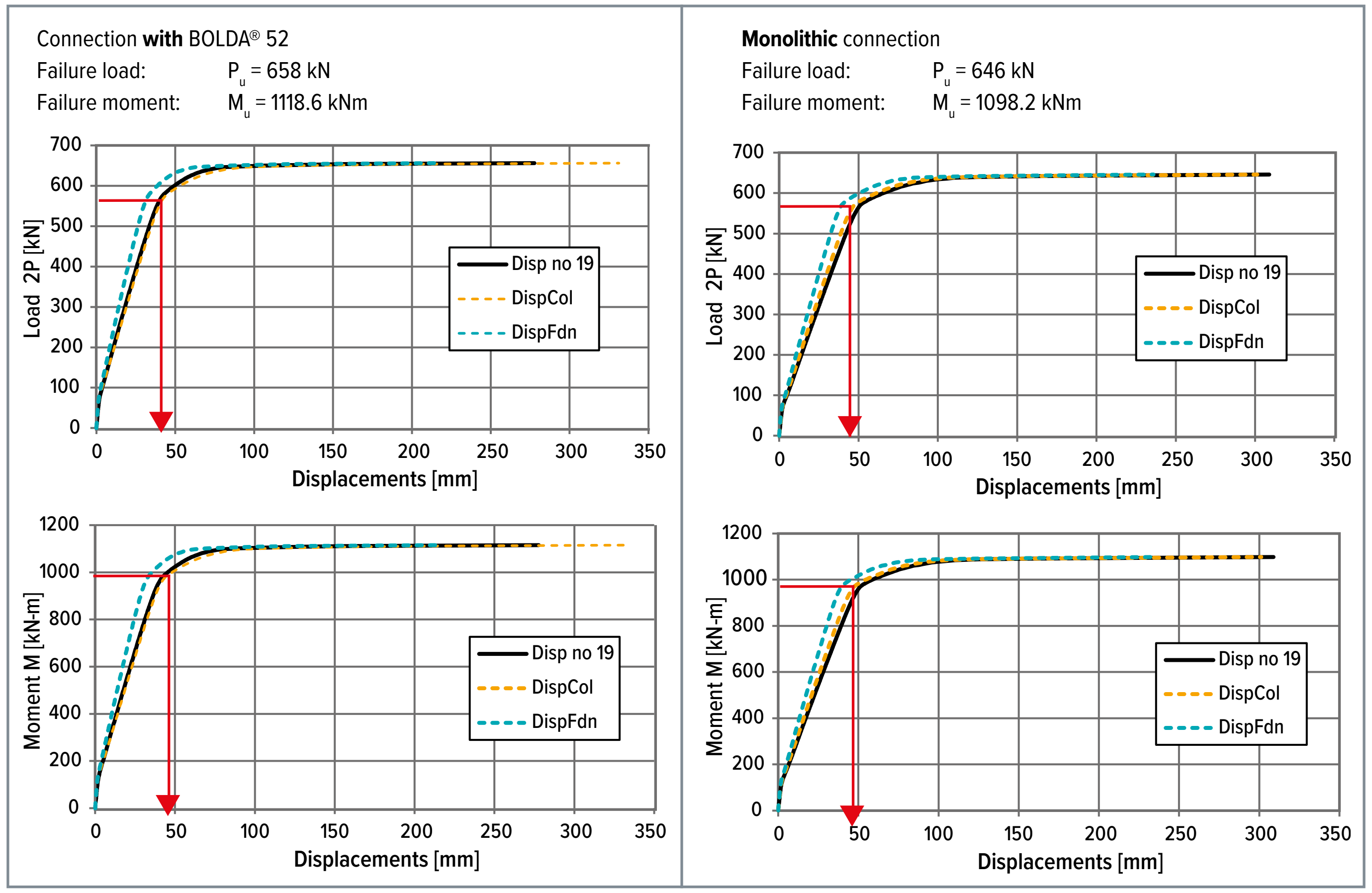


FIGURE 17: LOAD/MOMENT-DISPLACEMENT BEHAVIOR – CONNECTION WITH BOLDA® 52 COMPARED TO MONOLITHIC CONNECTION

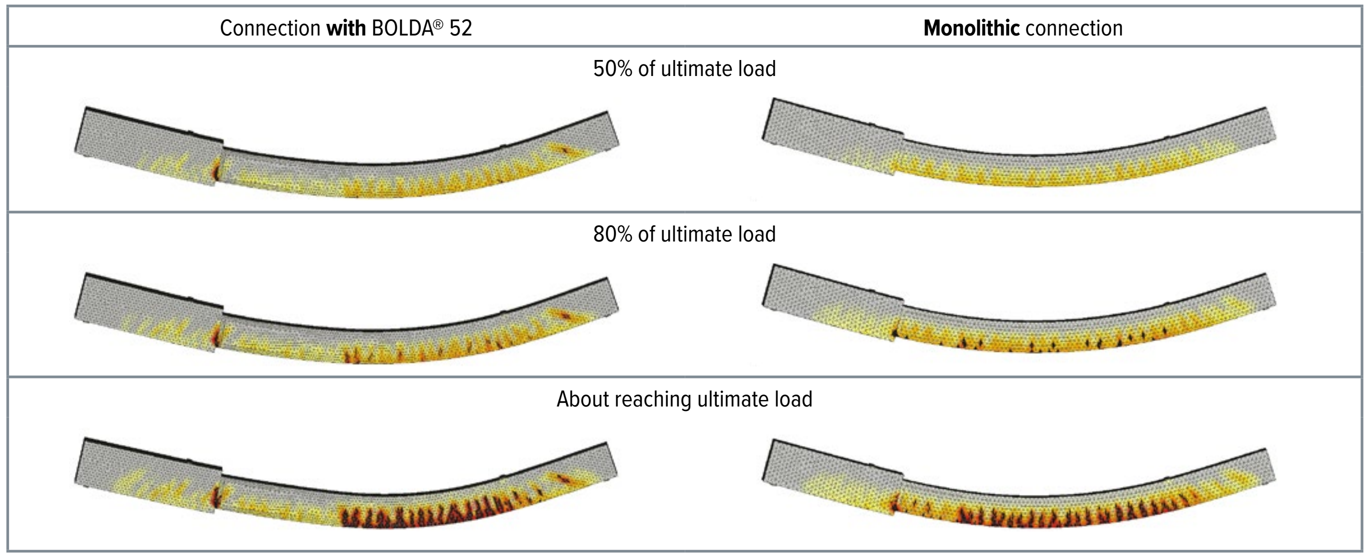
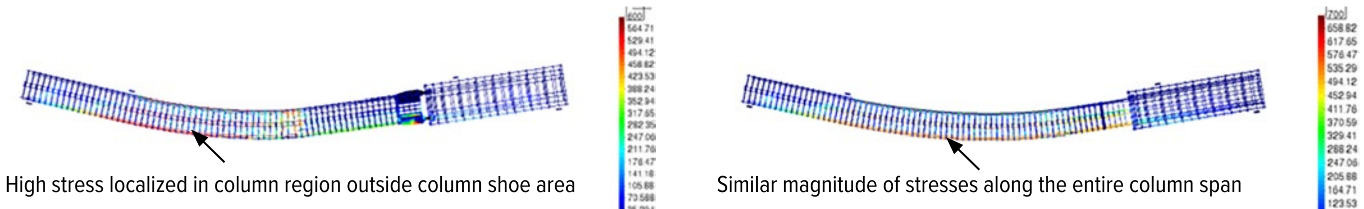


FIGURE 18: CRACK PATTERN COMPARED TO MONOLITHIC CONNECTION [18]



A) COLUMN SHOE SYSTEM (HIGH STRESS LOCALIZED IN COLUMN REGION OUTSIDE COLUMN SHOE AREA)

B) MONOLITHIC SYSTEM (SIMILAR MAGNITUDE OF STRESSES ALONG THE ENTIRE COLUMN SPAN)

FIGURE 19: STRESS DISTRIBUTION WITHIN THE ANCHOR BOLTS, COLUMN SHOE AND REINFORCEMENT AT FAILURE, BOLDA® 52 [18]

	BOLDA® 30			**BOLDA® 52**		
Subzone i	M_i	Column A	Column B	M_i	Column A	Column B
		$(EI)_i$	$(EI)'_i$		$(EI)_i$	$(EI)'_i$
	kNm	[MNm²]	[MNm²]	kNm	[MNm²]	[MNm²]
7	90	18.30	18.07	412	147.05	142.95
6	181	23.80	15.23	835	184.00	128.37
5	188	29.60	15.56	872	233.57	120.10
4	200	28.77	15.48	923	224.66	114.66
3	211	29.61	12.66	973	248.73	136.18
2	222	27.33	8.76	1023	220.30	146.80
1	234	8.73	4.41	1073	102.57	79.68
$1.0 \cdot M_{t,0}$	239			1098		
Deflection		v_{shoe}	v_{ref}		v_{shoe}	v_{ref}
		[mm]	[mm]		[mm]	[mm]
		77	129		172	226
v_{shoe}/v_{ref}		0.61			0.76	

TABLE 5: COMPARISON OF BENDING STIFFNESSES IN DIFFERENT SUBZONES AND CALCULATED DEFLECTIONS AT THE TOP OF THE COLUMNS – EVALUATION OF FE-RESULTS [18]

The ultimate stage of the column shoe system is characterized by yielding of the PPM® bolts (Figure 19 a). At this stage, the stress in the reinforcement outside of the column shoe area is in the range of σ ≤ 500 MPa. Within the monolithic system, at the ultimate failure load, the maximum stresses occur within the reinforcement in the entire column area between the end of foundation and the loading point (see Figure 19 b).

The bending moment in each subzone and the related stiffnesses in the middle of each subzone, as well as the maximum bending moment at the bottom of the column are calculated according to the procedure described in the previous section. The results are summarized in Table 5.

Figure 20 and Figure 21 show the distribution of the bending stiffness along the column axis related to the bending stiffness of the undisturbed region (subzone 7). In zone 2, the stiffness of precast column A is for both sizes of BOLDA® column shoes significantly higher compared to the cast-in-situ columns. In Zone 3, the relative stiffness of precast column A is smaller than the value obtained for column B. Nevertheless, the higher stiffness of zone 2 will compensate for the lower stiffness in zone 3.

The calculated deflection at the top of the columns based on the measured deformations are v_{shoe} = 77 mm (BOLDA® 30) and v_{shoe} = 172 mm (BOLDA® 52). These values are ca. 39% (BOLDA® 30) and 24% (BOLDA® 52) lower than the reference values of the cast-in-situ columns. Therefore, the results of the FE calculations confirm the test results. Thus, such FE-models are perfectly suited **to support the development of future column shoe systems** both quickly and efficiently. In addition, detailed parameter studies can be carried out.

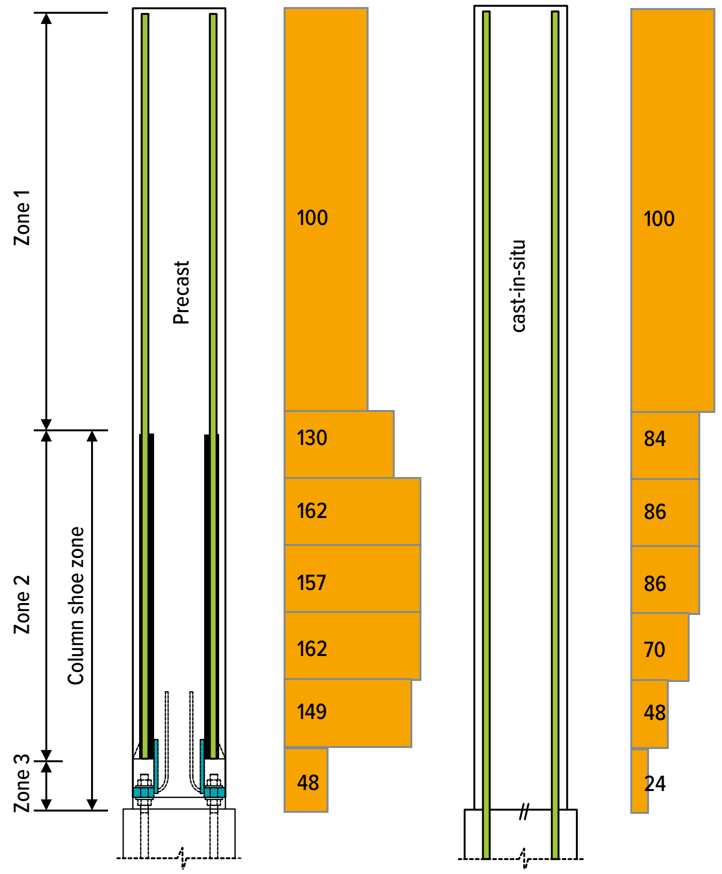


FIGURE 20: EVALUATION OF FE RESULTS FOR COLUMNS A (BOLDA® 30) AND B – RELATIVE BENDING STIFFNESS OF SUBZONES IN %

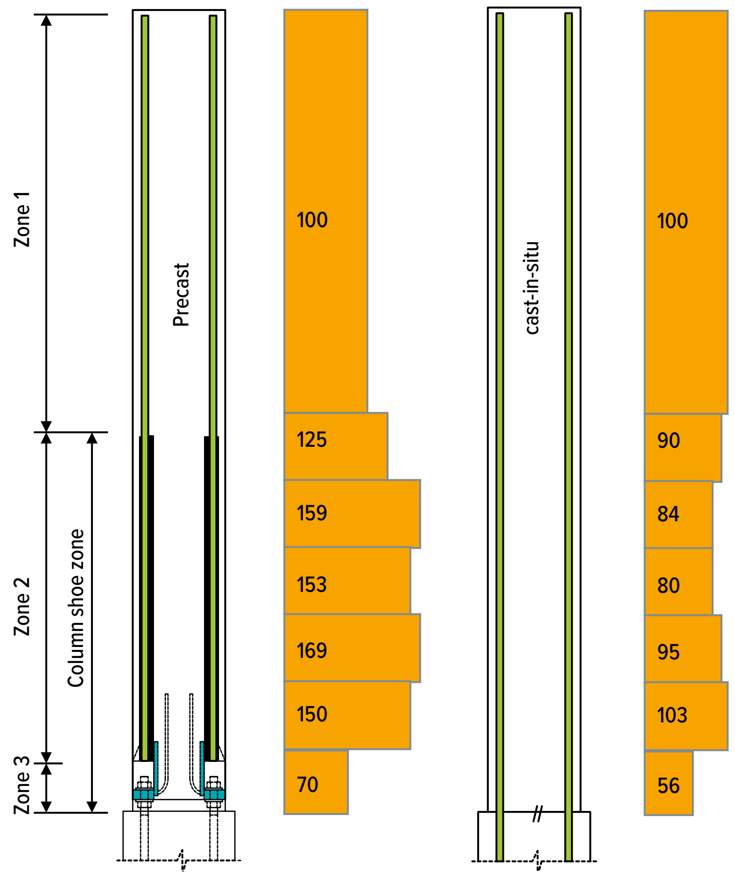


FIGURE 21: EVALUATION OF FE RESULTS FOR COLUMNS A (BOLDA® 52) AND B – RELATIVE BENDING STIFFNESS OF SUBZONES IN %

FIRE RESISTANCE

To determine temperatures in case of fire, fire tests on 3 test specimens (BOLDA® 30, BOLDA® 39 and BOLDA® 52) have been conducted at Technical University of Kaiserslautern [12, 13]. In addition, fire simulations using finite element method (FEM) were carried out on five column shoe sizes.

The temperatures determined should serve as a basis for design in the event of fire. The determination of the temperature is based on TR 068 [2]. The results of the fire tests [12] are compared with the results of the FEM simulation [13], and the respective temperatures in case of fire are derived at the critical points of the connection after 30, 60, 90, and 120 minutes of fire duration.

The specimens under consideration consist of a reinforced concrete column connected to a reinforced concrete foundation by means of BOLDA® column shoes and PPM® anchor bolts. The geometry of the test specimens for the fire tests, as well as the FE analysis is shown schematically in Figure 22. The measuring points in the tests correspond to those shown in Figure 22. These measuring points TE14 and TE15 were used for further evaluation.

The dimensions of the column and the foundation, the thickness of the joint, and the combination of column shoes and anchor bolts are given in Table 6. The dimensions of the columns and foundations correspond to the respective required minimum values.

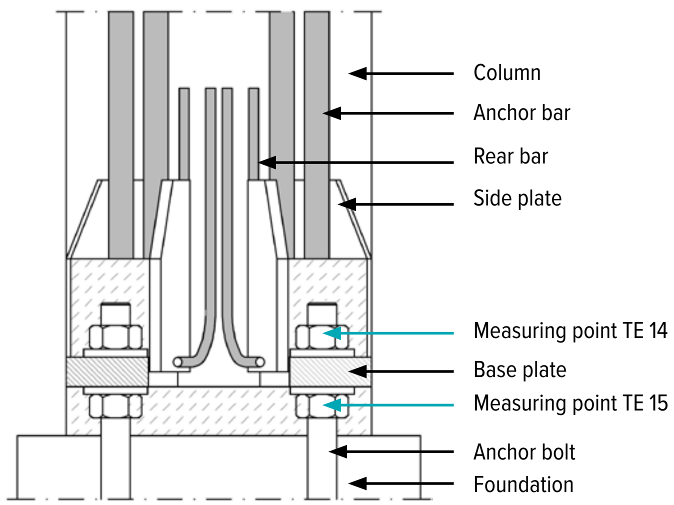
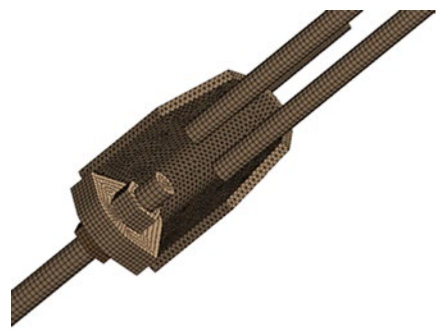


FIGURE 22: OVERVIEW OF THE CRITICAL SECTION

Column shoe	Anchor bolt	Column	Foundation	Joint thickness
		mm x mm	mm x mm	mm
BOLDA® 30	PPM 30 P	310 x 310	410 x 410	50
BOLDA® 36	PPM 36 P	360 x 360	460 x 460	55
BOLDA® 39	PPM 39 P	390 x 390	490 x 490	60
BOLDA® 45	PPM 45 P	450 x 450	550 x 550	65
BOLDA® 52	PPM 45 P	500 x 500	600 x 600	70

TABLE 6: SIZES OF COLUMN SHOE AND ANCHOR BOLTS AND CORRESPONDING MINIMUM CONCRETE SECTIONS [12]

A) COMPLETE SPECIMEN



B) BOLDA® 30 COLUMN SHOE AND ANCHOR BOLT PPM® 30 P

FIGURE 23: EXAMPLE OF THE FINITE ELEMENT MODEL [13]

The column connection was subjected to thermal stress using the standard fire curve according to DIN EN 1363-1 [16]. The test setup within the fire chamber is shown in Figure 24. Test specimens after completion of the fire tests are shown in Figure 25. It can be clearly seen that the greatest damage in the form of concrete spalling occurs at the points with the highest heat input, and at the same time with the smallest concrete volume – i.e. at the corners of the columns. It is important to note that no damage occurs in the area of the column shoe connection.

The results of the finite element calculation are summarized in [13]. Figure 26 shows exemplarily the results for BOLDA® 39 after a duration of 120 min.

Figure 26 clearly indicates that the maximum temperature appears on the outer faces of the column shoe base plate and the lower area of the side plate. The highest temperature of the anchor bolt is inside the base plate.

The comparatively lower temperatures in the anchor bars and the rear bars indicate that the fire resistance of the entire system is predominantly influenced by the temperature in the anchor bolt at the level of the anchor plate nearby the anchor bolt.

For all connections, the calculated temperature of anchor bolt section, as well as the measured temperature of tested anchor bolts, all at time points 30, 60, 90, and 120 minutes, are evaluated. Next, the difference between the **measured** temperatures and **calculated** temperatures at TE14 or TE15 is calculated for BOLDA® 30, BOLDA® 39, and BOLDA® 52.

FIGURE 24: TEST SPECIMENS IN THE COMBINED FIRE FURNACE AND ARRANGEMENT OF THE FURNACE THERMOCOUPLES [12]

FIGURE 25: TEST SPECIMENS AFTER COMPLETION OF THE FIRE TESTS

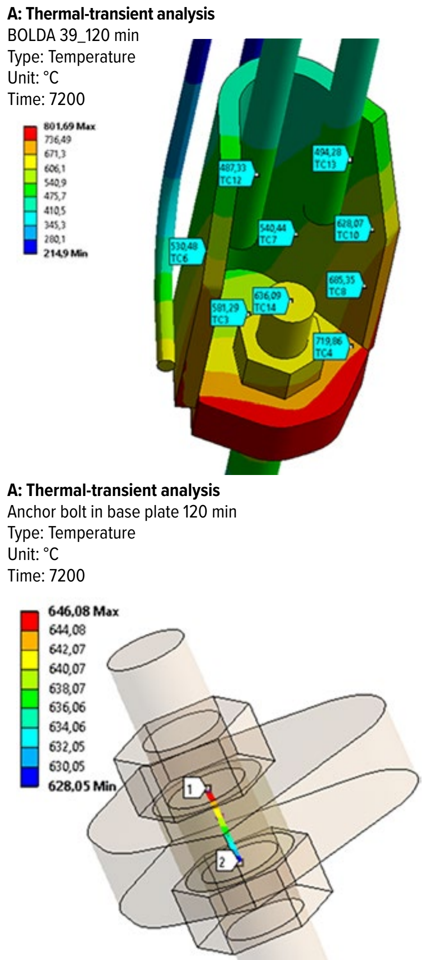


FIGURE 26: TEMPERATURE DISTRIBUTION IN COLUMN SHOE BOLDA® 39 AFTER 120 MIN [13]

Time	BOLDA® 30	BOLDA® 36	BOLDA® 39	BOLDA® 45	BOLDA® 52
min	°C	°C	°C	°C	°C
30	206	171	182	178	147
60	387	336	349	340	293
90	530	475	488	470	412
120	641	588	594	571	508

TABLE 7: RESULTING TEMPERATURES FOR FIRE DESIGN OF BOLDA® COLUMN SHOE CONNECTIONS

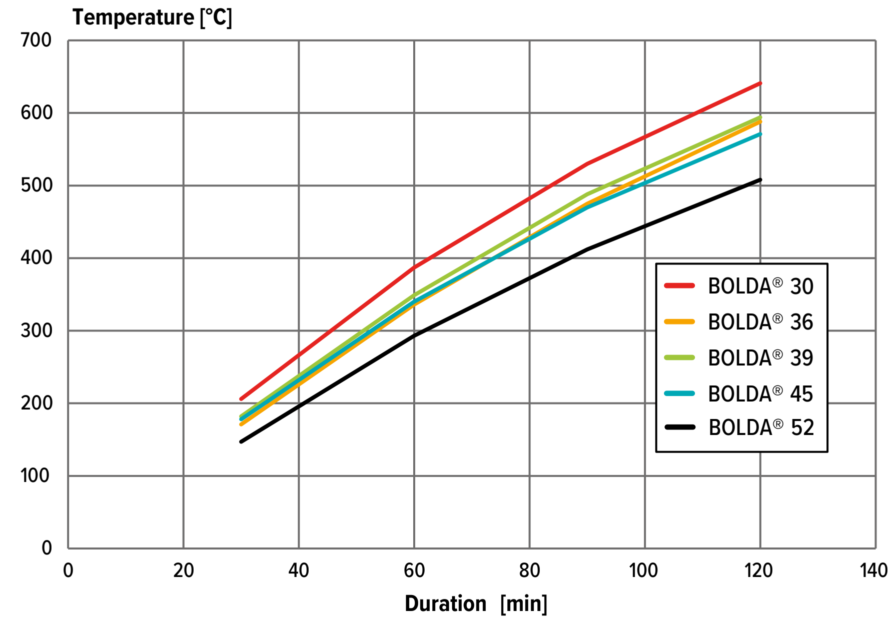


FIGURE 27: TIME-TEMPERATURE CURVES AT THE ANCHOR BOLT OF BOLDA® COLUMN SHOE CONNECTIONS [14]

The mean value of the mean differences is then calculated from the differences at the TE14 and TE15 positions. The mean difference between **the test results** and the **results of the FE calculation** determined in this way enable the calculation of the temperature in the anchor bolt at the level of the base plate below the upper nut. Therefore, the temperature of the bolt from the FEM simulation is reduced by the mean difference. For the BOLDA® 36 and 45 column shoes, this is done using the mean value of the neighboring column shoe sizes. The resulting temperatures are given in Table 7 and visualized in Figure 27. Table 7 and Figure 27 show that with increasing size of the column shoes in general the resulting temperature in the bolt decreases. For the three intermediate sizes this effect is less pronounced.

SUMMARY OF THE TEST RESULTS

The evaluations of the test results in the sections above clearly indicate that the design methods for column shoe connections given in the EAD are valid for BOLDA® column shoes. Furthermore, it was shown that the load bearing behavior, as well as the deformations of a precast column containing BOLDA® column shoes do not differ from the behavior of cast-in-situ columns of the same dimensions and reinforcement layout.

BOLDA® column shoes and column connections fulfil all requirements according to EAD regarding mechanical, fire, and corrosion resistance. Design of column connections with BOLDA® column shoe connections is included in Peikko Designer® to facilitate daily tasks of structural engineers.

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