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# Large Scale Buckling Tests of Bar Bundle Columns

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## Abstract

Bar bundle columns are a new type of composite column. For this purpose, a bundle of high-strength reinforcing bars with a yield strength of 670 N/mm² is set in a steel tube and then grouted with mortar.

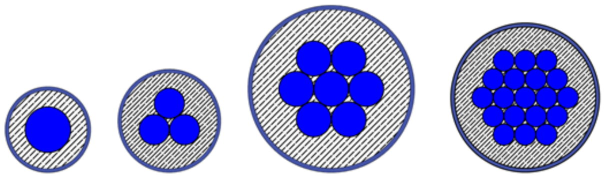
Due to the lower cross-sectional thickness of the threaded bars, no strength reduction due to material thickness effects is required compared to a solid core cross-section. The bundling of the steel bars results in a high steel content in relation to the total cross-section; as a result, the novel composite column achieves load-bearing capacities that are usually typical for columns with significantly larger cross-sectional dimensions. In addition, bar bundle columns exhibit better heating behavior compared to composite columns with solid cross sections, as the bars only touch at certain points. As part of the AiF research project IGF- 20352 N, 10 buckling tests with lengths between 3.5 m and 8 m were carried out. Cross sections with 1, 3, 7 and 19 bars as core were investigated. The experimental setup, the measurement technique and the results are shown here.

## Keywords

composite columns, stability, buckling tests, high strength steel

## 1 New types of composite columns

Bar bundle columns are a new type of composite column. For this purpose, a bundle of high-strength reinforcing bars with a yield strength of 670 MPa is placed in a steel tube and then grouted with mortar. Due to the lower cross-sectional thicknesses of the threaded bars, no strength reduction due to material thickness effects is present compared to a solid core cross section. The bundling of the steel bars results in a high steel content in relation to the total cross section.



bars 1xØ75
tube 139,7x5

bars 3xØ50
tube 168,3x5

bars 7xØ57,5
tube 273x6

bars 19xØ35
tube 244,5x6,3

**Figure 1** Various bar bundle column cross sections

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As a result, the novel composite column achieves load-bearing capacities that are usually typical for columns with significantly larger cross-sectional dimensions [1]. The bars are arranged in a circular pattern depending on the bar diameter and the required concrete cover, resulting in cross-sections with 1, 3, 7 or 19 bars (see Figure 1) or even more. In this project, no larger diameters than 273 mm are examined. Bar bundle columns show good heating behaviour comparing to solid sections [2], as bars only have very limited local contact. The bundling of the column's core generates a defined more complex manufacturing process, compared to current state-of-the-art composite columns. To ensure economic success, aspects of design and manufacturing methods, therefore also had be taken into account during development. [3]

## 2 Test setup

Within the scope of the AiF research project IGF- 20352 N "bar bundle columns", 10 large-scale buckling tests were carried out to analyze the stability behavior of this new type of composite columns and to develop a reliable design concept.

The following test configurations (see Table 1) were chosen to investigate a wide range of related slenderness ratios and cross-section configurations. The columns were each fabricated with a 40 mm thick head and foot plate to ensure direct load transfer into the core section.



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Table 1 Test configurations

| No.: | Tube [mm] | Length of the tube [mm] | Number of bars [-] | Diameter of the bars[mm] | Related slender-ness [-] |
|---|---|---|---|---|---|
| **KRT-1** | 139.7x5.0 | 3500 | 1 | 75 | 1.74 |
| **KRT-2** | 168.3x5.0 | 3500 | 3 | 50 | 1.52 |
| **KRT-3** | 219.1x6.3 | 5550 | 3 | 75 | 1.89 |
| **KRT-4** | 273.0x6.0 | 3500 | 7 | 57,5 | 0.96 |
| **KRT-5** | 244.5x6.3 | 3500 | 19 | 35 | 1.08 |
| **KRT-6** | 273.0x6.0 | 5550 | 7 | 57,5 | 1.52 |
| **KRT-7** | 244.5x6.3 | 5550 | 19 | 35 | 1.71 |
| **KRT-8** | 273.0x6.0 | 7950 | 7 | 57,5 | 2.16 |
| **KRT-9** | 244.5x6.3 | 7950 | 19 | 35 | 2.44 |
| **KRT-10** | 323.9x6.0 | 3500 | 19 | 50 | 0.86 |

The tubes for the test specimens were made of S355, except for test specimen KRT-2 where S235 was used. The mortar used for grouting the composite columns was a CEM I R (ep) with a compressive strength of approx. 80 MPa and an young's modulus of approx. 21000 MPa.

### 2.1 Static system and loading

The tests were carried out at the Ruhr University in Bochum, since a test machine with a maximum load of 20 MN and a maximum test specimen length of 10 m is available there. (see Figure 2)

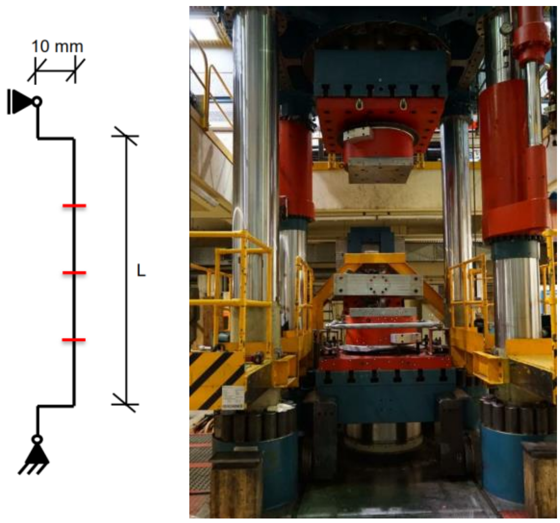


**Figure 2** Static system of experiments and the experimental machine

Euler case 2 with a planned eccentricity of 10 mm at the top and bottom in the X-direction was chosen as the static system for the test (see Figure 2). This offered a defined buckling direction for the column and was helped to install measurement equipment efficiently. The hinged bearing was realized by spherical bearings at the top and bottom with very little frictional resistance.

The loading procedure of the columns was carried out following the instructions in Annex B of EC 4-1-1, which specifies requirements for the testing of composite elements and composite slabs [4] (see Figure 3). This procedure was already used experimental tests in [5],[6] and [7].

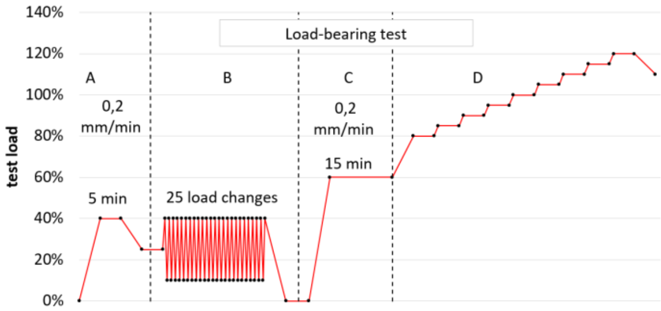


**Figure 3** Load progression of the test specimens

### 2.2 Measuring procedure

Prior to the tests, all test specimens were recorded using a 3D scanner to determine the global eccentricities in the X and Y directions. Thus, the length difference, the pre-curvatures, the ~~eccentricities at the top~~ and the bottom and the inclinations of the head plates were recorded (see Figure 4).

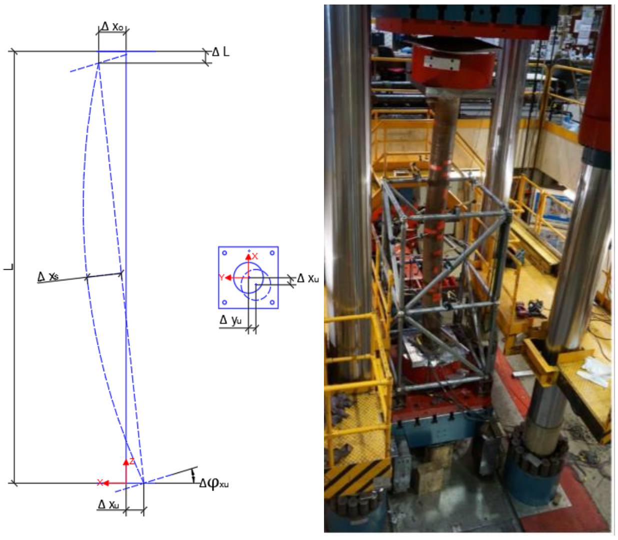

**Figure 4** Global eccentricities in the X and Y directions and load test

In order to record the load-bearing behavior of the column, various strains and movements were recorded in addition to the machine load, the machine travel and the bearing rotations. Measurement planes were defined at the quarter points of the column (see Figures 2 and 5). By specifying the buckling direction, the maximum deformations and strains could be recorded. The deflection of the column was recorded in the X and Y directions in the measuring planes. The strain gauges (see Figure 5, marked in red) were arranged in such a way that the maximum stresses of the tube and also of the core bars could be recorded.

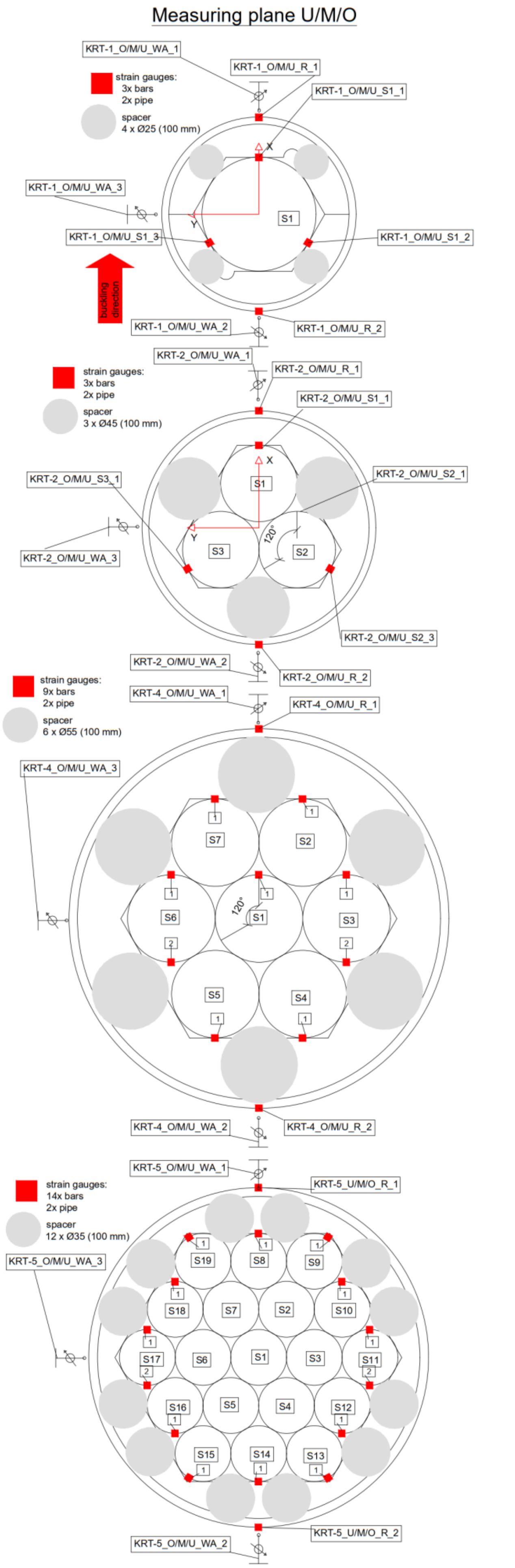


**Figure 5** Measurement arrangement for different cross-section configurations

## 3 Test results

Table 2 shows the maximum load from the tests, the maximum deflection at the center, the moment at the center at maximum load, and the experimentally determined bending stiffness of the test specimens at maximum load.

**Table 2** Test results of the bar bundle columns

| No.: | Max. load [kN] | Deflection at max. load [mm] | Moment in the middle at max. load [kNm] | Stiffness in the middle at max. load [kN/m²] |
|---|---|---|---|---|
| **KRT-1** | 1296.67 | 14.84 | 15.15 | 15350.40 |
| **KRT-2** | 1497.23 | 31.31 | 60.26 | 2630.93 |
| **KRT-3** | 2290.85 | 39.28 | 130.33 | 9837.94 |
| **KRT-4** | 8603.50 | 31.60 | 326.64 | 15589.30 |
| **KRT-5** | 6961.28 | 32.97 | 319.41 | 13467.90 |
| **KRT-6** | 4222.43 | 48.14 | 248.03 | 18556.80 |
| **KRT-7** | 3377.42 | 59.67 | 228.72 | 11951.80 |
| **KRT-8** | 2258.62 | 70.79 | 163.47 | 19677.20 |
| **KRT-9** | 1851.20 | 79.21 | 147.82 | 12901.10 |
| **KRT-10** | 18580.31 | 32.17 | 834.50 | 38260.80 |

The force-deflection curves of the tests can be seen in Figure 6. For this purpose, the deflection at the center of the column in the X direction or buckling direction was used.

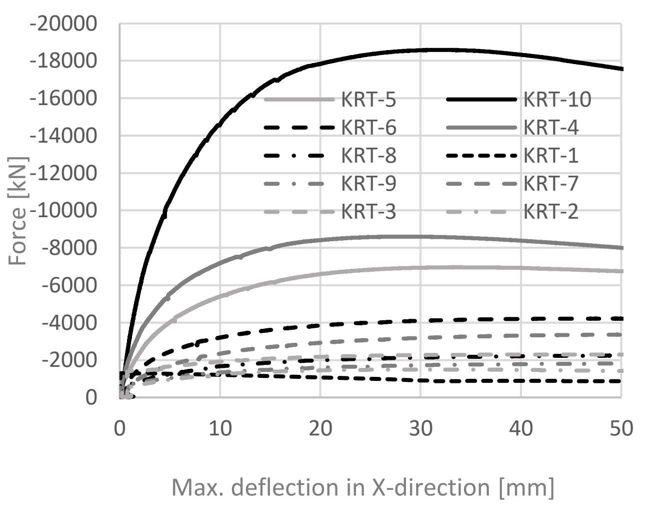


**Figure 6** Force-deflection curves of the tests

The moment $M(F)$ of the test specimens was determined as a function of the surcharge load $F$ using the following formula.

$$M(F) = F \cdot \Delta x_O + F \cdot e_x + F \cdot \Delta x_S + F \cdot u(F) \quad (1)$$

The moment is composed of the following four components, the unplanned measured misalignment $\Delta x_O$ (see Figure 4), the planned load eccentricity $e_x$ (see Figure 2), the maximum measured pre-curvature $\Delta x_S$ (see Figure 4) and the column deflection measured during the test $u(F)$ (see Figure 6). Figure 7 shows the load-moment curve of the KRT-2 column.

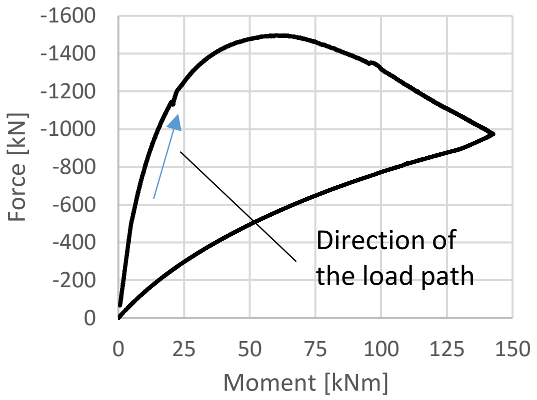


**Figure 7** Load moment curve of test KRT-2

The experimental bending stiffness can be derived from the moment-curvature relationship (2), but this relationship assumes that the cross-section is planar and that the Bernoulli hypothesis holds.

$$EI_{exp} = \frac{M(x)}{\kappa_M} \tag{2}$$

Figure 8 shows the strains of the middle measuring plane at maximum load, the strains form almost one plane, therefore a plane strain state can be assumed.

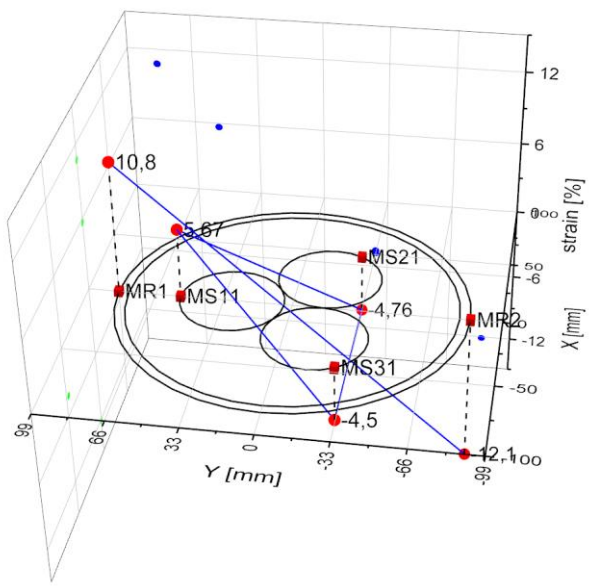


**Figure 8** Strain distribution at ultimate load in the middle of the column of test KRT-2

The curvature of the cross-section $\kappa_M$ can therefore be calculated using formula (3). $\varepsilon_{M-R-1}$ and $\varepsilon_{M-R-2}$ are strains, measured on opposite sides of the tube, d is the diameter of the entire cross-section.

$$\kappa_M = \frac{\varepsilon_{M-R-1} - \varepsilon_{M-R-2}}{d} \tag{3}$$

Figure 9 shows the force-bending stiffness curve of the KRT-2 column, with the bending stiffness plotted at maximum load. The experimentally determined bending stiffness increases strongly at the beginning of the test and decreases as soon as the materials start to plasticize and/or the concrete starts to cracks. The minimum bending stiffness is reached at maximum load.

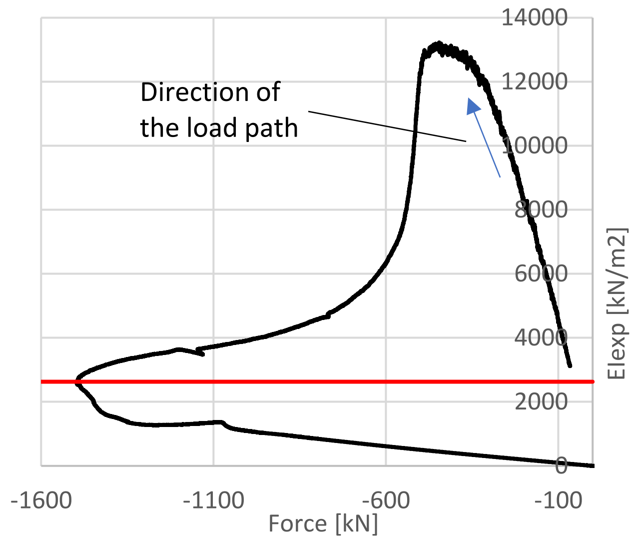


**Figure 9** Experimental bending stiffness over acting normal force of test KRT-2

## 4 Conclusion

The tests on the stability behavior of bar bundle columns show promising results. In the further course of the project, the data will be further analyzed and evaluated. With the help of the data, a FE model of the column will be calibrated and various parameter studies will be carried out to investigate the influence of the individual components. The integration into existing design concepts will be done last.

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