# Experimental database of the deformations and stiffness of headed shear studs in solid concrete slabs

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**Keywords**

Design standard; Ductility; Elastic slip; Concrete slabs; Headed studs; Load-slip curves; Shear connection; Slip capacity; Steel-concrete composite structures; Stiffness

**Abstract**

This article presents load-slip measurements for headed shear studs in solid concrete slabs from 180 push tests described in 16 studies dating from 1956 to 2017. The database also includes the elastic slip, slip capacity, and shear stiffness determined from the load-slip curves in accordance with the second generation of Eurocode 4 (prEC4), and the slip capacity and shear stiffness per AISC 360. The prEC4-related variables were determined using the prEC4 stud resistance model and the SRD1 and SRD2 resistance models developed by the present authors, which outperform all existing models. Statistical parameters of the database variables, their distributions, and correlations are presented and discussed in the article. The dataset provides the basis for identifying the key variables affecting stud deformations and developing models for predicting the load-slip response,  elastic slip, slip capacity, and stiffness of headed shear studs in solid concrete slabs. This information is crucial for evaluating the stud ductility and stiffness, which affect the shear force distribution in steel-concrete composite structures and their resistance, stiffness, and ductility.

## Introduction

The resistance, stiffness, and ductility of steel-concrete composite structures depend on the shear force distribution in shear connectors. The load-slip response of the shear connectors determines the force distribution. The existing design standards for steel-concrete composite structures identify the importance of shear connection ductility and stiffness without providing guidelines for their estimation in design. The existing experimental data accumulated over six decades were collected in the presented database to facilitate the analysis of the parameters affecting the shear stiffness and ductility and the development of predictive models.

The presented data is useful for identifying design variables affecting the stud deformations, classifying the ductility of shear stud connections and their stiffness, and developing new predictive models. In addition, the data forms the basis for realistic considerations of shear connection deformations, ductility, and stiffness in analytical and numerical studies of steel-concrete composite structures, contributing to safer and more economical design rules, benefiting researchers and practitioners working in the field of composite steel and concrete structures.

## Data description

The dataset [1] was collected from 16 publications dating from 1956 to 2017, with the previously published databases of shear stud resistance [2] and [3] taken as the basis. The publications referenced in the database describe test specimens, materials, and methods used in each test program. The tests included in the database were identified through a comprehensive literature review using the following selection criteria: 1) sufficient information about the measured material and geometric properties of the studs and concrete was provided; 2) there was no poor stud welding, low concrete strength, or unexpected test problems reported; and 3) experimental load-slip curves were presented.

The dataset [1] presents load-slip measurements for headed shear studs in solid concrete slabs from 180 tests, as well as over ten measured and nominal parameters of the test specimens. The elastic slip, slip capacity, and shear stiffness determined from the load-slip data in accordance with the second generation of Eurocode 4 (prEC4) [4] are also presented, as well as the shear stiffness and slip capacity obtained following the AISC 360 [5] provisions.

According to prEC4 [4], the elastic slip, slip capacity, and shear stiffness are determined as follows:

- The elastic slip, $\delta_e$, is computed as $\delta_e = s_e/0.7$, where $s_e$ is the slip at $0.7P_{Rk}$, and $P_{Rk}$ is the characteristic stud resistance.
- The slip capacity, $\delta_u$, is taken as the slip within the falling branch of the load-slip curve at $P_{Rk}$.
- The shear stiffness, $k_{sc}$, is calculated as $k_{sc} = 0.7P_{Rk} / s_e$.

AISC 360 [5] recommends determining the slip capacity, $s_u$, at $0.95P_u$ after the peak load, $P_u$, was reached and the shear stiffness, $k_{sc}$, in the load range between $0.10P_u$ and $0.40P_u$.

The elastic slip, slip capacity, and shear stiffness according to prEC4 [4] were computed for the prEC4 stud resistance model and the SRD1 and SRD2 models [6], which were developed by the present authors and demonstrated better performance than the existing models. Furthermore, the shear stiffness, $k_{sc}$, for the prEC4 framework was determined at the $0.5P_{Rk}$ and $0.7P_{Rk}$ load levels, representing the serviceability limit state (SLS) and the ultimate limit state (ULS), respectively [7].

The dataset is presented within a Microsoft Excel file in the XLSM format with three worksheets. The first worksheet, entitled "Database," contains the dataset. The second worksheet, "References," provides bibliographic references to the publications used for the dataset collection. The third worksheet, "Notation," defines the variables. The dataset is also provided in the JSON format.

The dataset includes the mean measured shear resistance per stud, $P_{em}$, and the following nine measured parameters:

- concrete compressive strength, $f_{cm}$;
- concrete secant modulus of elasticity, $E_{cm}$;
- concrete density, $\rho$;
- ultimate tensile strength of studs, $f_{um}$;
- diameter of stud shank, $d_m$;
- weld collar diameter, $d_{dom}$;
- weld collar height, $h_{wm}$;
- stud height after welding, $h_m$; and
- the stud height-to-diameter ratio, $h_m/d_m$.

The following nominal properties required for reliability analyses in accordance with the Eurocodes are also presented in the dataset:

- the characteristic compressive cylinder strength, $f_{ck}$ ($f_{lck}$), in accordance with EN 1992-1-1 [8];
- concrete secant modulus of elasticity, $E_{cm}$ ($E_{lcm}$), calculated from $f_{ck}$ ($f_{lck}$) in accordance with EN 1992-1-1 [8];
- density class for lightweight concrete in accordance with EN 1992-1-1 [8];
- concrete density, $\rho$, in accordance with EN 1992-1-1 [8];

- ultimate tensile strength of studs, $f_u$, in accordance with EN ISO 13918 [9];
- stud shank diameter, $d$;
- weld collar diameter, $d_{do}$;
- weld collar height, $h_w$;
- the stud height-to-diameter ratio, $h/d$; and
- specified as-welded stud height, $h$.

The total number of studs, $n$, and the position of slab reinforcement measured downwards from the top of the stud, $z_s$, are also presented. The readers are referred to [10] and [11] for additional information on how the $f_{cm}$, $E_{cm}$, $d_{dom}$, $h_{wm}$, and $f_{ck}$ values were obtained.

The database provides the following variables for the prEC4 [4], SRD1 [6], and SRD2 [6] stud resistance models based on the prEC4 [4] method:

- characteristic resistance per stud, $P_{Rk}$;
- shear connection stiffness per stud for the SLS, $k_{sc,SLS}$;
- shear connection stiffness per stud for the ULS, $k_{sc,ULS}$;
- elastic slip for the ULS, $\delta_{e,ULS}$;
- slip capacity, $\delta_u$; and
- the length of the idealized elastic-perfectly plastic load-slip relationship plateau, $\delta_u$- $\delta_{e,ULS}$.

For the AISC 360 [5] method, the shear connection stiffness per stud, $k_{sc}$, and the slip capacity, $s_u$, are presented.

The shear stiffness and slip values were determined from the load-slip measurements also provided in the dataset. The load-slip measurements were obtained by digitizing load-slip curves from the considered publications.

The statistical parameters of the database variables are presented in Table 1, whereas Fig. 1 illustrates distribution plots.

Table 1 indicates that the database covers a wide range of design variables characterized by 25.1 MPa $\leq f_{cm} \leq$ 115.8 MPa, 406.8 MPa $\leq f_{um} \leq$ 675.0 MPa, 12.7 mm $\leq d_m \leq$ 31.8 mm, 3.0 $\leq h_m/d_m \leq$ 9.1, and -165 mm $\leq z_s \leq$ 55 mm (N.B. negative values of $z_s$ indicate that the reinforcement was positioned above the top of the stud). Both normal weight concrete (NWC) and lightweight concrete (LWC) were included in the database, with 162 and 18 specimens, respectively.

Figs. 2 to 5 show correlation matrices for the considered methods and resistance models. They indicate that the elastic slip and slip capacity do not correlate strongly with independent variables. The prEC4 [2] shear stiffness at the ULS and the AISC 360 [5] shear stiffness show a strong correlation only with $f_{cm}$, unlike the shear stiffness at the SLS, which correlates with the independent variables moderately or weakly. Strong correlations between $f_{cm}$ and $E_{cm}$ together with $E_{cm}$ and $\rho$ exist. However, it should be noted that in many tests, the $E_{cm}$ values were either unreported or determined from the measured $f_{cm}$ values in accordance with the *fib* Model Code [12], which explains the strong correlation between $f_{cm}$ and $E_{cm}$.

Figs. 6 to 9 present regression plots with the red lines denoting linear regression lines and the shaded bands around the regression lines representing regression estimates with a 95% confidence interval.

**Table 1**
Statistical parameters of the database variables

| Variable | Min | Max | Mean | Standard Deviation | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| $P_{em}$ (kN) | 47.6 | 330.1 | 185.5 | 60.6 | 0.07 | -0.41 |
| $f_{cm}$ (MPa) | 25.1 | 115.8 | 68.2 | 29.6 | 0.22 | -1.40 |
| $E_{cm}$ (GPa) | 13.7 | 46.5 | 34.6 | 8.0 | -1.22 | 1.00 |
| $\rho$ (kg/m$^3$) | 1657.9 | 2423.0 | 2329.6 | 209.8 | -2.68 | 5.45 |
| $f_{um}$ (MPa) | 406.8 | 675.0 | 516.2 | 47.1 | 0.17 | 0.82 |
| $d_m$ (mm) | 12.7 | 31.8 | 21.2 | 2.9 | 0.31 | 1.71 |
| $d_{dom}$ (mm) | 17.0 | 44.5 | 27.3 | 4.1 | 0.64 | 2.13 |
| $h_{wm}$ (mm) | 3.0 | 8.6 | 5.8 | 0.9 | -0.29 | 1.80 |
| $h_m$ (mm) | 75.0 | 200.0 | 115.2 | 35.9 | 1.26 | 1.08 |
| $h_m/d_m$ | 3.0 | 9.1 | 5.4 | 1.5 | 1.18 | 0.81 |
| $z_s$ (mm) | -165.0 | 55.0 | -33.1 | 47.3 | -1.56 | 2.18 |
| $P_{Rk,prEC4}$ (kN) | 33.9 | 226.2 | 127.0 | 37.5 | 0.24 | -0.03 |
| $\delta_{e,prEC4,ULS}$ (mm) | 0.2 | 2.7 | 0.5 | 0.4 | 2.69 | 10.50 |
| $\delta_{u,prEC4}$ (mm) | 1.3 | 22.6 | 8.4 | 3.5 | 0.88 | 1.41 |
| $k_{sc,prEC4,ULS}$ (kN/mm) | 37.0 | 749.6 | 343.6 | 180.3 | 0.02 | -1.12 |
| $k_{sc,prEC4,SLS}$ (kN/mm) | 48.0 | 1702.6 | 444.9 | 249.4 | 0.92 | 2.67 |
| $P_{Rk,SRD1}$ (kN) | 42.6 | 299.2 | 142.0 | 50.6 | 0.50 | 0.27 |
| $\delta_{e,SRD1,ULS}$ (mm) | 0.2 | 2.8 | 0.6 | 0.3 | 2.95 | 13.23 |
| $\delta_{u,SRD1}$ (mm) | 1.3 | 21.9 | 8.3 | 3.5 | 0.88 | 1.13 |
| $k_{sc,SRD1,ULS}$ (kN/mm) | 28.2 | 612.3 | 314.0 | 149.0 | -0.08 | -1.16 |
| $k_{sc,SRD1,SLS}$ (kN/mm) | 45.1 | 929.1 | 403.8 | 190.3 | 0.03 | -0.68 |
| $P_{Rk,SRD2}$ (kN) | 42.6 | 299.2 | 142.0 | 50.5 | 0.51 | 0.26 |
| $\delta_{e,SRD2,ULS}$ (mm) | 0.2 | 2.8 | 0.6 | 0.3 | 2.93 | 12.88 |
| $\delta_{u,SRD2}$ (mm) | 1.3 | 21.9 | 8.3 | 3.5 | 0.88 | 1.13 |
| $k_{sc,SRD2,ULS}$ (kN/mm) | 26.7 | 612.3 | 313.9 | 149.2 | -0.09 | -1.16 |
| $k_{sc,SRD2,SLS}$ (kN/mm) | 43.0 | 929.1 | 403.7 | 190.4 | 0.03 | -0.68 |
| $s_{u,AISC}$ (mm) | 1.3 | 15.1 | 7.3 | 2.6 | 0.40 | 0.25 |
| $k_{sc,AISC}$ (kN/mm) | 47.5 | 785.0 | 362.5 | 177.3 | 0.16 | -0.70 |

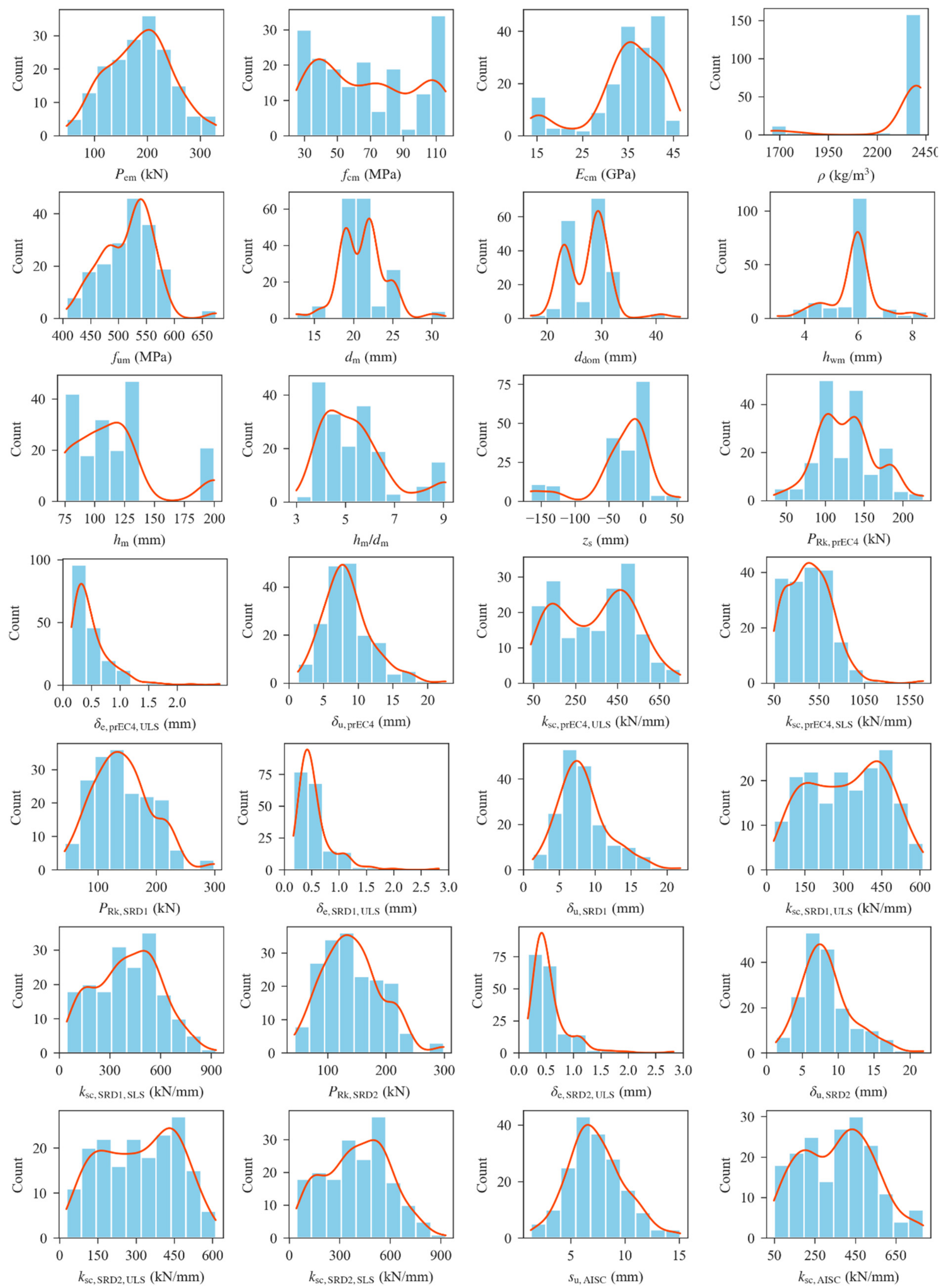

**Fig. 1.** Distributions of database variables

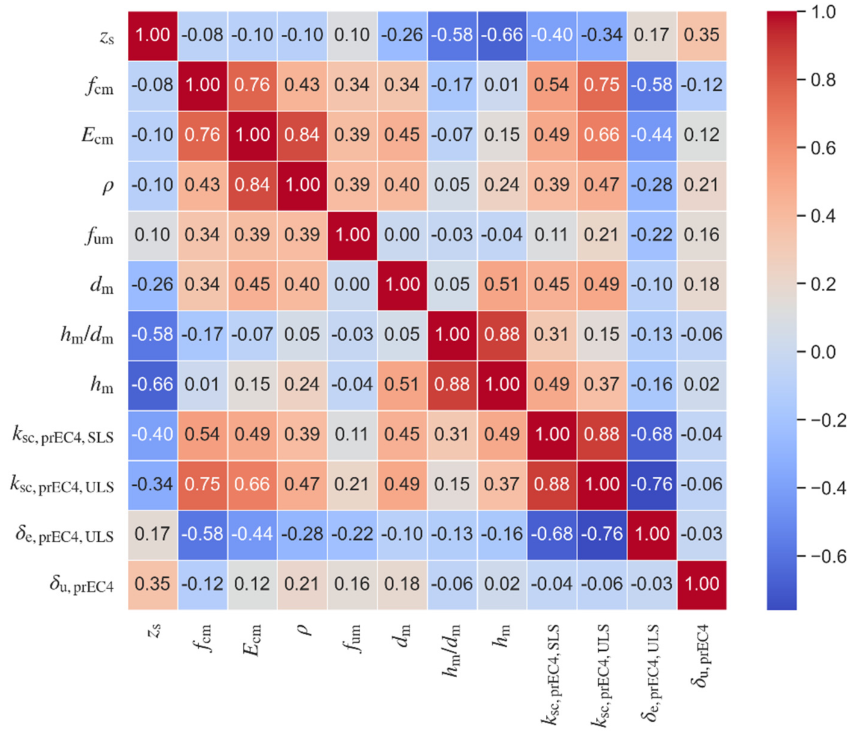

**Fig. 2.** Correlation matrix for the prEC4 [4] method and the prEC4 [4] resistance model

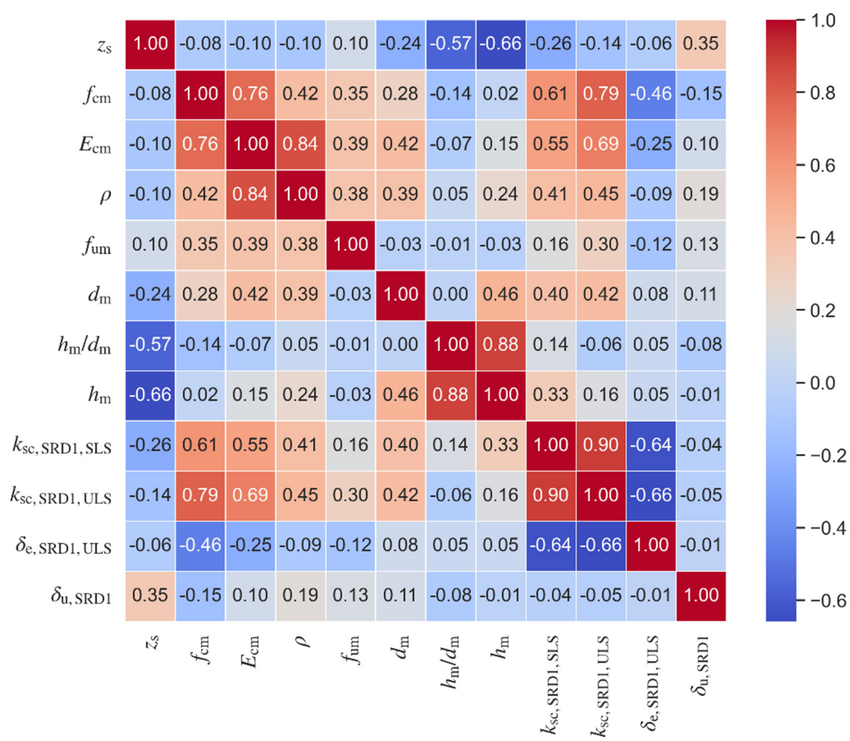

**Fig. 3.** Correlation matrix for the prEC4 [4] method and the SRD1 [6] resistance model

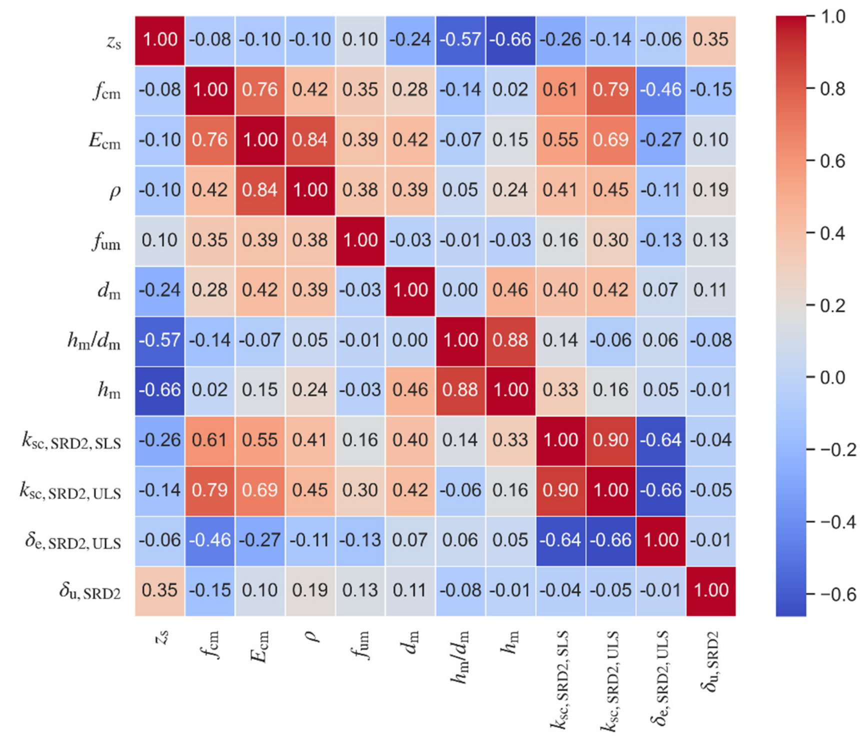


**Fig. 4.** Correlation matrix for the prEC4 [4] method and the SRD2 [6] resistance model

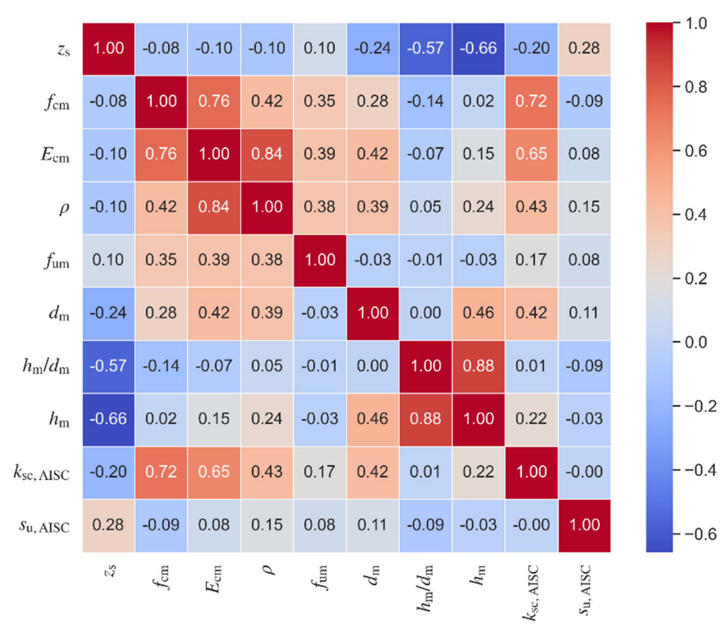


**Fig. 5.** Correlation matrix for the AISC 360 [5]

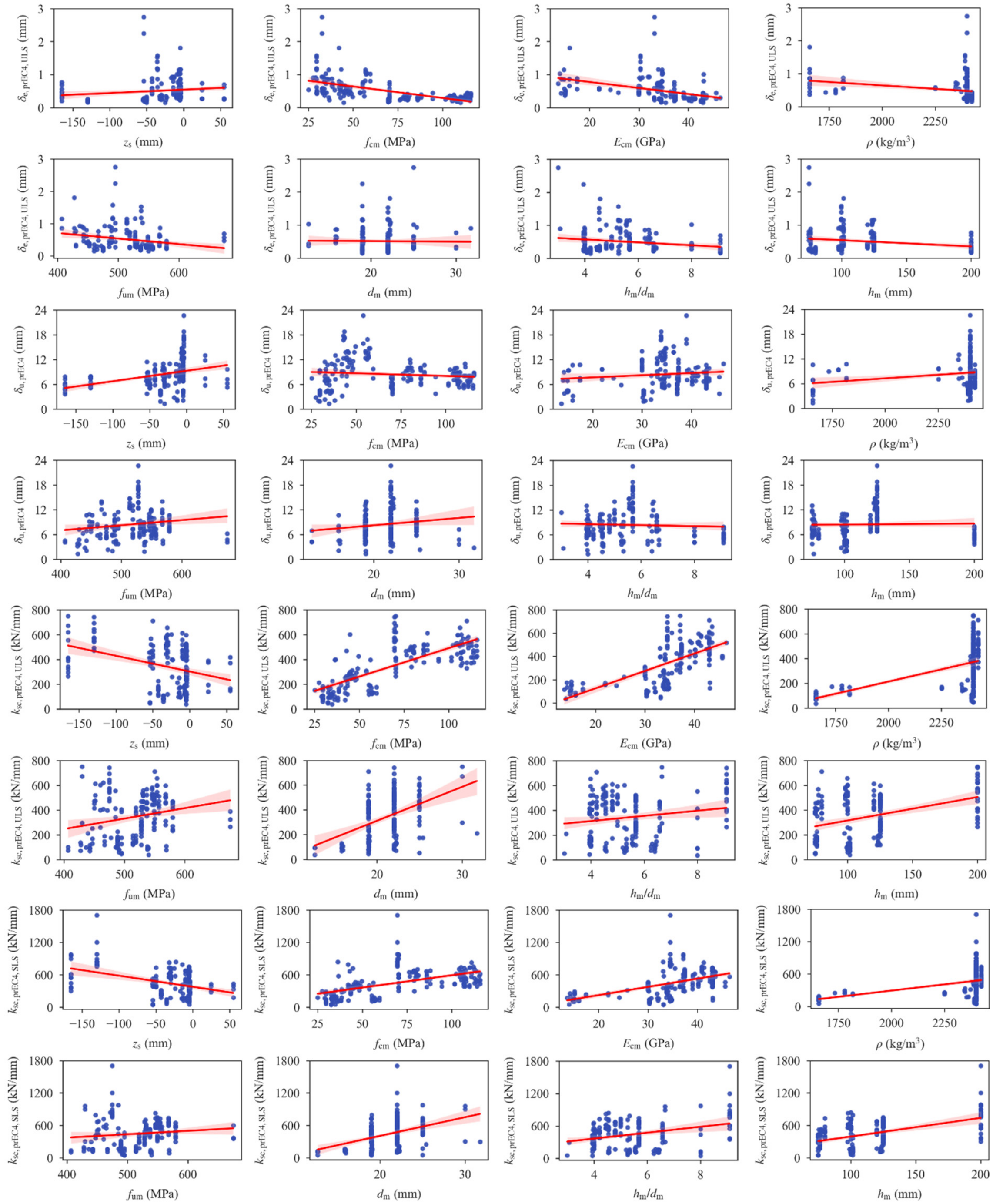

**Fig. 6.** Regression plots for the prEC4 [4] method and the prEC4 [4] resistance model

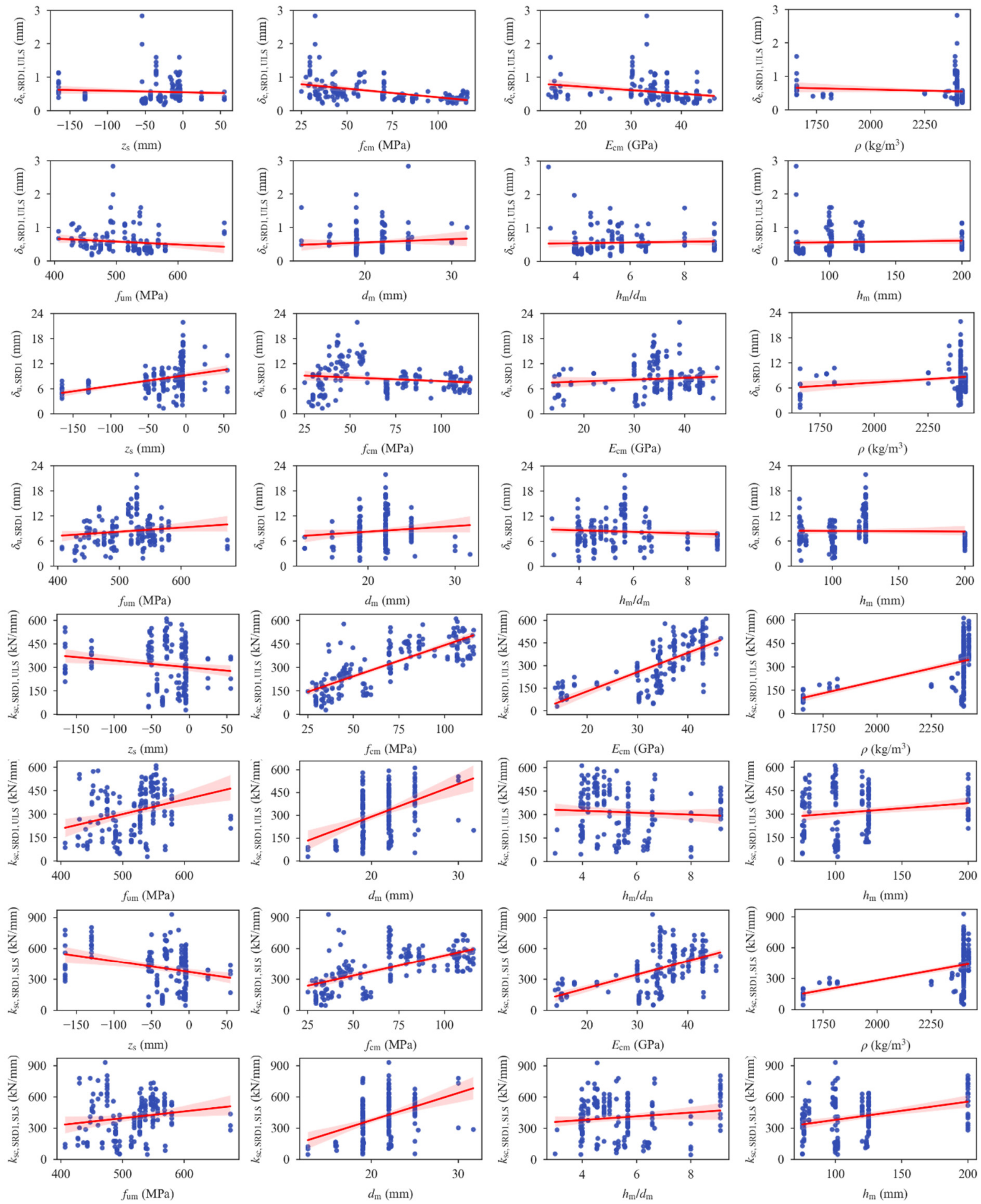

**Fig. 7.** Regression plots for the prEC4 [4] method and the SRD1 [6] resistance model

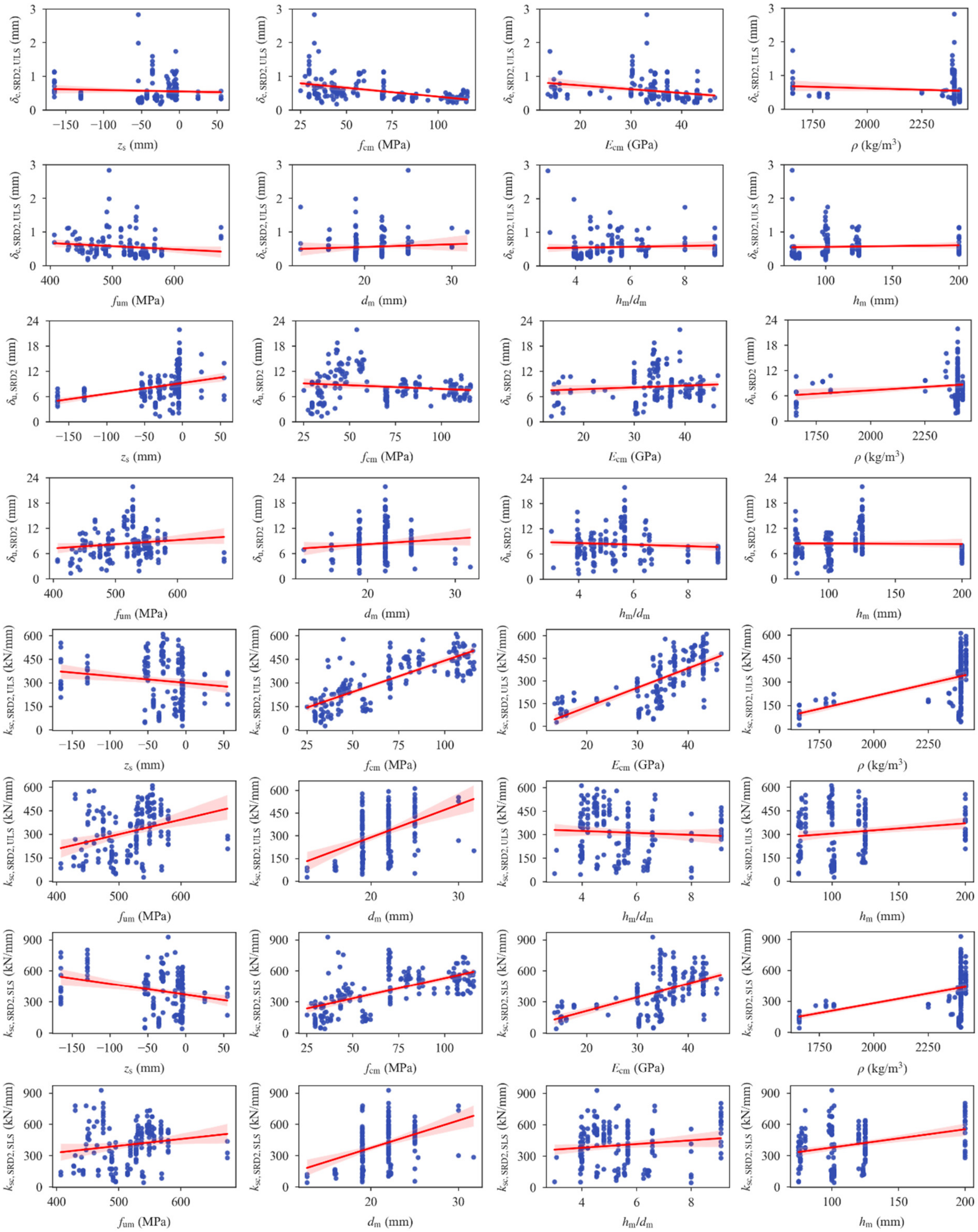


**Fig. 8.** Regression plots for the prEC4 [4] method and the SRD2 [6] resistance model

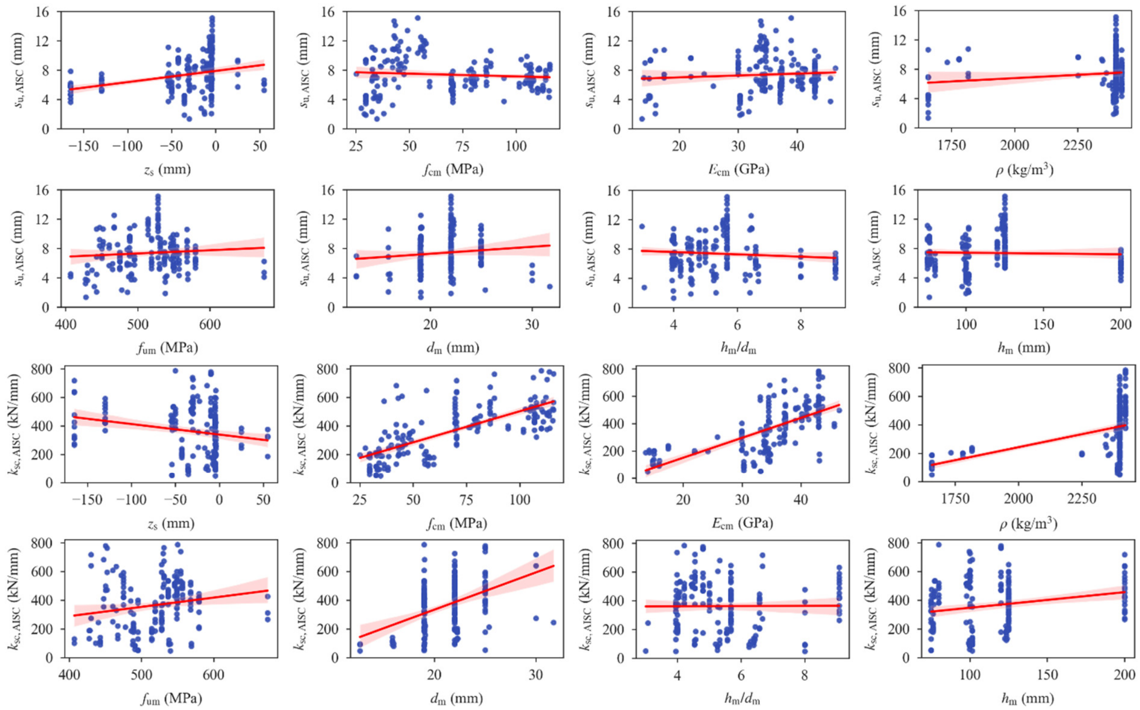

**Fig. 9.** Regression plots for the AISC 360 [5] method

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