Stochastic simulations of headed-stud shear connections in profiled composite floors

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Abstract

In this study, recycled aggregate concrete (RAC) is applied on the top of profiled steel decking to form composite slabs, working together with steel beams via commonly used headed-stud shear connections. The authors used advanced finite element (FE) simulations to reveal the load-bearing behaviour (i.e., load capacity, slip modulus, deformation capacity, and failure modes) of headed-stud RAC connections. Prior to simulations, the FE model is verified by available shear tests on headed-stud connections using natural aggregate concrete (NAC). Deterministically, the headed-stud RAC and NAC connections have similar load-bearing behaviour, providing that there is negligible difference in the strength of RAC and NAC. However, the high variability of mechanical properties of RAC is an essential safety concern for structural applications. To address the influence of uncertainty (high variability) of RAC mechanical properties on the resistance of headed-stud shear connections, stochastic functions are established with polynomial chaos expansion technique based on results of advanced FE simulations. The stochastic functions are used to generate a database of resistance of a pool of headed-stud connection models containing random properties of RAC. With the database of headed-stud RAC connections, one can perform reliability analyses for calibrating partial safety factors in the future design model.

1. Introduction

The construction industry is a significant contributor to emissions and waste, with a notable portion stemming from the disposal of construction and demolition materials in landfills. This situation poses challenges for achieving sustainable development. A potentially impactful remedy lies in recycled aggregate concrete (RAC), which utilises recycled construction and demolition waste to markedly curtail waste production. Despite its potential, RAC currently lacks widespread and efficient utilisation. Applying RAC on top of steel beam-supported profiled sheeting to form composite floor systems is a solution to bolster the adoption of RAC and foster a more efficient circular economy within the construction sector. The integrity of floor systems is achieved by headed stud connectors between composite slabs and steel beams. Therefore, the design and load-bearing behaviour of headed-stud connections are vital to composite structures. The design equations for headed-stud connections in profiled slabs using natural aggregate concrete (NAC) are supposed to be revised in the second generation of Eurocode 4 [1] for better accuracy, owing to many push-out tests (e.g., [2–6]) available in the past decades. The revised equations may not be applicable for headed-stud connections in RAC composite floor systems, since the properties of RAC have higher variability compared to that of NAC. However, the current database of headed-stud RAC connections is too small (ZERO) to perform reliability analyses for calibrating design equations. To fill this gap, the authors intend to initiate the database with a dozen of experimental tests complemented with advanced finite element (FE) simulations and establish stochastic functions with polynomial chaos expansions (PCE). The stochastic functions can connection using NAC in Vigneri [4]. The validated advanced FE modelling was used to simulate headed-stud connections sampled with the Latin Hypercube Sampling (LHS) method, considering three basic variables, i.e., headed stud height h_{sc}, concrete cylinder strength f_c, and stud ultimate strength f_u. They are deemed following normal distributions based on prior knowledge. The other factors such as the diameter of the stud (d=19 mm), the height of the profiled steel sheeting (h_p=58 mm), and widths of the rib (b_{bottom}=62 mm, b_{top}=101 mm) were kept constant to simplify illustrating the construction of PCE functions in the present conference paper. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the design of the headed-stud connections subjected to push tests in this study.

Resistance of a headed-stud connection (function $R(X)$ in Eq. 1), a random variable, is represented by a polynomial chaos expansion (stochastic part) of independent random variables (***X***) and coefficients c_j (deterministic part).

$$R(\boldsymbol{X}) = \sum_{j=0}^{N-1}(c_j \cdot \prod_{i=1}^{M} H_i\,(x_i)) \quad (1)$$

where the variables ***X***= {x_1, …, x_i, …, x_M} indicate random variables h_{sc}, f_c, and f_u, and M is certainly equal to 3. H_i (x_i) is the orthonormal Hermite Polynomial of x_i, as x_i follows standard normal distributions. N is the number of terms of the polynomial expansions (R(X)), determined by a truncation order p and the number of variables M, with $N = (M+p)!/M!/p!$ [7]. Coefficients c_j can be computed with data points of properly designed experiments. Then, the PCE function in Eq. (1) is established.

3. Results and Discussions

3.1 Validation of FE modelling

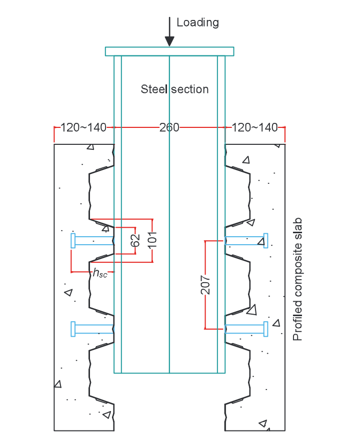


Fig. 1 Headed-stud connection under load

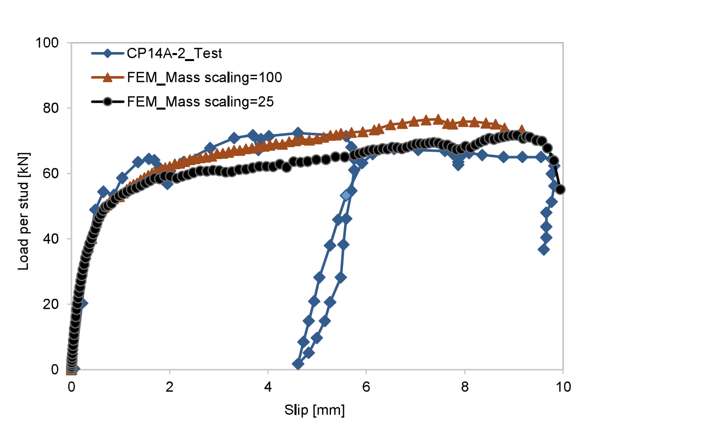
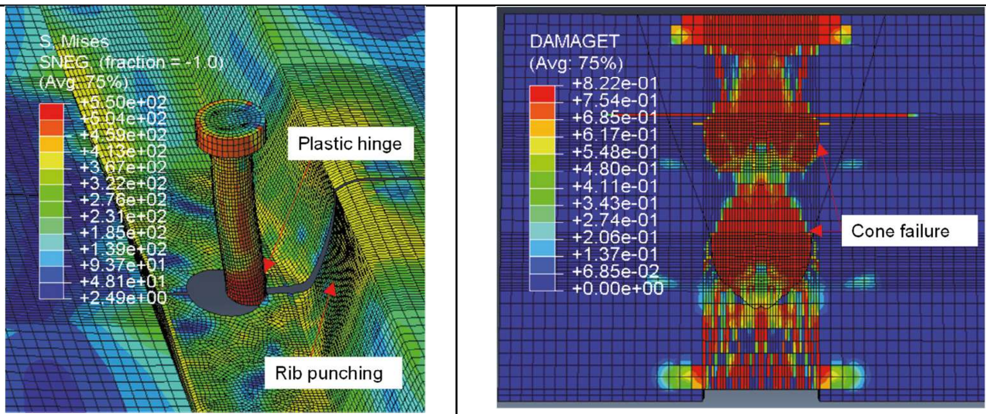


Fig. 2 Comparison of load-slip curves between test and FE simulations

The test specimen CP14A-2 in Vigneri [4] was simulated with the above modelling method for validation. Specifically, the specimen has a concrete cylinder strength of 49.7 MPa, ultimate strength of headed-stud of 551 MPa, stud diameter of 19 mm, and stud height of 98 mm. The other material strength and geometry can be found in Vigneri [4] to reduce the paper length. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the comparison of the load-slip curve between the test result and FE simulations, where mass scaling factors of 100 and 25 were respectively used to trade between modelling accuracy and computation time. Both models can predict the development of the load-slip curve with an acceptable deviation. So, a mass scaling factor of 100 was selected in the following FE stochastic simulations. Moreover, the failure mode was well captured by the FE model, i.e., profiled rib punching (Fig. 3 a) and pull-out failure of concrete cones (Fig. 3 b), accompanied by a plastic hinge at the stud root (Fig. 3 a).



(a) Plastic hinge in studs (b) Horizontal section view of concrete slab

Fig. 3 Failure mode of the headed-stud connection under push-out loading

3.2 Results of FE simulations

Twenty-two headed-stud connection random models were designed, sampling (LHS) random variables h_{sc}, f_c, and f_u from the ranges of 76 – 124 mm, 20 – 68 MPa, and 400 – 500 MPa, respectively. It was assumed that the sampling ranges cover 99.7% of the variable values, i.e., 3 standard deviations from the means. It is worth mentioning that the variable ranges can be defined as smaller or wider flexibly, provided that the constructed PCE functions work well compared with validating results. Based on the designs, the models were simulated, and the maximal load-bearing capacities (P_e in kN/stud) are shown in Table 1.

Table 1 Stochastic FE simulation results of headed-stud connections

Nr.	h_{sc}	f_c	f_u	P_e	Nr.	h_{sc}	f_c	f_u	P_e	Nr.	h_{sc}	f_c	f_u	P_e
1	102.1	47.3	448.7	**68.6**	9	110.3	42.5	445.8	**58.2**	17	112.4	48.9	436.1	**71.2**
2	100.9	43.9	432.8	**64.0**	10	88.9	44.2	444.6	**62.2**	18	91.9	49.4	455.8	**59.3**
3	96.0	58.8	429.6	**61.7**	11	93.6	57.5	442.0	**62.2**	19	106.9	43.7	457.7	**66.7**
4	95.4	49.8	465.4	**59.8**	12	105.7	37.8	428.3	**54.0**	20	105.1	54.5	447.7	**70.8**
5	98.7	54.9	474.6	**57.9**	13	97.9	42.0	405.6	**56.7**	21	83.7	59	431.3	**56.1**
6	107.4	44.4	443.1	**63.6**	14	103.7	49.7	439.9	**68.5**	22	87.4	44.7	456.6	**48.9**
7	102.9	60.8	476.1	**77.8**	15	110.9	40.9	440.6	**62.0**					
8	104.8	57.0	462.3	**67.2**	16	106.4	48.7	457.1	**67.0**					

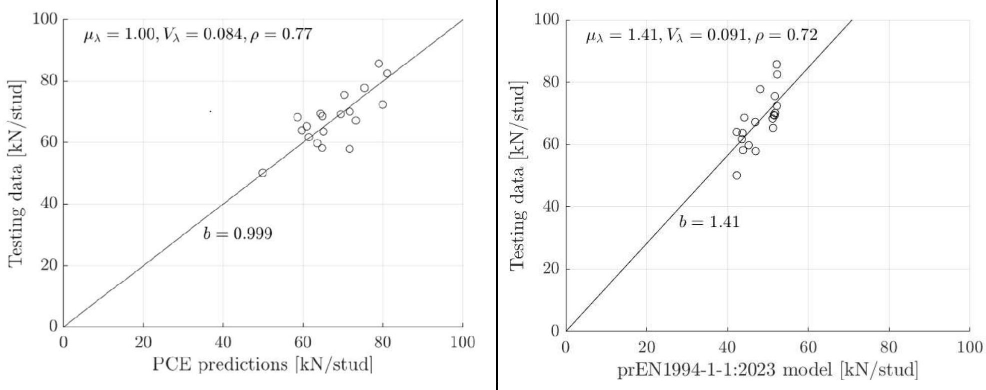
3.3 Construction and evaluation of PCE functions

The variables and resistance of models Nrs.12-22 (Table 1) and CP14B, CP14C, and CP14D series from [4] were used to fit coefficients c_j, yielding the PCE function $R(\boldsymbol{X}) = 66.33 + 8.23x_1 + 11.74x_2 + 2.36x_3 - 0.50\ (x_1^2-1)/2^{1/2} - 4.01(x_2^2-1)/2^{1/2} + 0.29\ (x_3^2-1)/2^{1/2} - 1.24x_1x_2 + 0.79x_1x_3 + 1.70x_2x_3$. The results of Nrs.1-11 (Table 1) and CP12A, CP12C, and CP14A series from [4] were used to test the performance of the PCE function and the semi-empirical model in prEN1994-1-1

[1]. First, the correlation coefficient (ρ) between the PCE function and testing data is 0.77 (Fig. 4), showing a high positive correlation, which is slightly stronger than 0.72 of the prEN1994-1-1 model. Besides, the bias factors (a random variable) in Eq. (2) were statistically evaluated.

$$\lambda = \frac{Test\ result}{Model\ prediction} \tag{2}$$

As shown in Fig. 4, the mean values of the bias factors (μ_λ) of the PCE function and prEN1994-1-1 model [1] are 1.0 and 1.41, respectively. It indicates that the predictions of the PCE function are around the validating data and prEN1994-1-1 model predictions are on the conservative side. This can be also seen from the slopes *b* obtained from "Least Squares" best fit. The coefficients of variation of the bias factors (V_λ) of the PCE function and prEN1994-1-1 model are 0.084 and 0.091, indicating that the PCE function has slightly smaller uncertainty than the other.



(a) PCE function (b) prEN1994-1-1 model (characteristic)

Fig. 4 Statistical evaluations of PCE function and prEN1994-1-1 model

4. Conclusions

It is demonstrated that the PCE function can predict the resistance of headed-stud connections between steel beams and profiled composite slabs with independent random variables. The PCE function has a satisfactory accuracy and uncertainty compared to the semi-empirical model in prEN 1994-1-1:2023. Considering these advantages, the authors propose to use the data-driven PCE surrogate model for the design of structural members and for quantifying the resistance reliability (uncertainty) of structural members using RAC.

5. Acknowledgement

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