DATA-DRIVEN DESIGN OF HEADED-STUD CONNECTIONS IN STEEL-RECYCLED AGGREGATE CONCRETE COMPOSITE FLOORS USING POLYNOMIAL CHAOS EXPANSIONS

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1. INTRODUCTION

In the global construction industry, the consumption of aggregates for concrete is ever-increasing, accompanied by the growing outputs of construction and demolition waste (CDW) (Wang et al. 2021). Immoderate exploitation of natural resources and the disposal of CDW on land both jeopardize sustainable development. Recycling CDW into recycled aggregate is a feasible and economical way to close the loop of supply and waste chains. Due to the inferior mechanical properties and large variability of RAC, it has been mainly used in non-structural construction such as pavement. Extensive experimental investigations showed that it is feasible to use steel reinforced RAC and steel section-RAC composite members for structural applications, as summarized in review articles (Deresa et al. 2020; Li et al. 2015). However, design models for NAC (e.g., (EN 1992-1-1 2004)) may not have a satisfactory safety margin for RAC design, considering the variability of structural resistance of RAC members. This concern has not been clarified, since there were limited studies, e.g., Pacheco et al. (2020, 2021), addressing the suitability of the existing design models the RAC structures from the perspective of reliability. And the limited studies on reliability were only for reinforced concrete members, without covering steel-concrete composite members.

Steel-concrete composite slabs as a kind of secondary structural member are a good destination to promote massive applications of RAC. Shear connections between slabs and steel beams are vital to the performance of composite beams and further to the entire building. Therefore, it is crucial to quantify the uncertainty of resistance, e.g., load-bearing capacity, of commonly used headed-stud shear connections using RAC (abbr. headed-stud RAC connections), caused by high variability of RAC properties. To consider this uncertainty, the conventional way is to build a database of random resistance of headed-stud connections by analytical models or stochastic FE simulations verified by actual tests. Analytical models themselves usually have high uncertainty and stochastic simulations with accurate advanced FE models are extremely costive and time-consuming. Alternatively, polynomial chaos expansion (PCE) is widely used to quantify probabilistic uncertainty in engineering systems efficiently (Sudret 2007). In this study, PCE is used to build a mathematical surrogate model for data-driven design of headed-stud shear connections in steel-concrete composite floor systems.

2. MATERIALS AND METHODS

As shown in Eq. (1), PCE represents a random variable Y (herein is resistance) in terms of a polynomial function $\psi_{\boldsymbol{\alpha}}(\boldsymbol{X})$ of independent random variables ($\boldsymbol{X}$) multiplied with coefficients $c_{\boldsymbol{\alpha}}$.

$$Y = \sum_{\boldsymbol{\alpha} \in N^M} c_{\boldsymbol{\alpha}} \Psi_{\boldsymbol{\alpha}}(\boldsymbol{X}) \tag{1}$$

$$\Psi_{\boldsymbol{\alpha}}(\boldsymbol{X}) \stackrel{\text{def}}{=} \prod_{i=1}^{M} P_{\alpha_1}^{(i)}(x_i) \tag{2}$$

Herein the variables $\boldsymbol{X}= \{x_1, \ldots, x_i, \ldots, x_M\}$ indicate material properties and geometry of headed-stud connections, and M is the number of independent random variables. The array $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, \ldots, \alpha_i, \ldots, \alpha_M\}$ are multi-indices, indicating degree (α_i) of a monic polynomial $P_{\alpha i}^{(i)}$ of x_i. The polynomials $P_{\alpha i}^{(i)}$ (i=1, 2, …i, …M) are from the orthonormal family such as Hermite and Legendre. Specifically, if x_i follows a normal distribution, $P_{\alpha i}^{(i)}$ is a Hermite polynomial. If x_i follows a uniform distribution, $P_{\alpha i}^{(i)}$

is a Legendre polynomial. To obtain $P_{\alpha i}^{(i)}$, polynomial expansions need to be truncated at a certain order p. Then, the number of terms of $c_\alpha \psi_\alpha(\boldsymbol{X})$ in Eq. (1) turns to be $j = (M+p)!/M!/p!$ (Sudret 2007). Coefficients c_α need to be computed with properly designed experimental results.

For instance, based on the lead-bearing mechanisms and stud failure mode, stud diameter (d), stud height (h), stud ultimate strength (f_u) and concrete strength (f_c) are determined as the four basic variables (i.e., M=4). If a truncation order is defined as 3, $c_\alpha \psi_\alpha(\boldsymbol{X})$ has 35 terms (j=35). The four basic variables are regarded as following normal distributions according to prior knowledge. They need isoprobablistic transforms into standard normal distributions (x_1, x_2, x_3, x_4). The multivariate polynomials are arranged as follows: $\boldsymbol{\psi}_\alpha(\boldsymbol{X}) = \boldsymbol{\psi}_{j=35}(\boldsymbol{X}) = [1, x_1, x_2, x_3, x_4, (x_1^2-1)/2^{1/2}, (x_2^2-1)/2^{1/2}, (x_3^2-1)/2^{1/2}, (x_4^2-1)/2^{1/2}, x_1x_2, x_1x_3, x_1x_4, x_2x_4, x_2x_3, x_3x_4, (x_1^3-3x_1)/6^{1/2}, (x_2^3-3x_2)/6^{1/2}, (x_3^3-3x_3)/6^{1/2}, (x_4^3-3x_4)/6^{1/2}, x_2(x_1^2-1)/2^{1/2}, x_3(x_1^2-1)/2^{1/2}, x_4(x_1^2-1)/2^{1/2}, x_1(x_2^2-1)/2^{1/2}, x_3(x_2^2-1)/2^{1/2}, x_4(x_2^2-1)/2^{1/2}, x_1(x_3^2-1)/2^{1/2}, x_2(x_3^2-1)/2^{1/2}, x_4(x_3^2-1)/2^{1/2}, x_1x_2x_3, x_1x_2x_4, x_1x_3x_4, x_2x_3x_4]$. Based on the 192 test data points of headed-stud NAC connections controlled by stud failure , the coefficients c_α are solved out and presented in array $c_{j=35}$=[219.02, 19.74, -27.97, 34.79, 4.67, 17.10, 8.83, 1.35, 13.2, -10.82, -21.55, 25.78, -19.84, 7.08, -10.15, 0.69, -16.89, 8.04, 13.68, -13.04, 7.32, 6.30, 21.34, -50.54, 11.66, -20.03, -11.35, -23, 10.36, -16.60, 3.78, 18.10, -22.73, 20.59, 8.87]^T. The surrogate model turns out to be $\boldsymbol{M}(\boldsymbol{X}) = \boldsymbol{\psi}_{j=35}(\boldsymbol{X}) \cdot c_{j=35}$.

In turn, the statistic of the established PCE surrogate model is evaluated with the test data using the method in EN 1990 (2002). Additionally, the PCE model was used for analyses of headed-stud RAC connections, assuming that RAC does not change the failure mode of connections. Specifically, the authors compared the the resistance distributions of headed-stud connections using different concrete, i.e., NAC, and RAC with the respective 50% and 100% replacement of coarse aggregate. The four basic variables, i.e., d, h, f_u, and f_c, are normally distributed. The stud design is the same among the three designs of headed-stud connections, as shown in Table 1. The mean values (μ) and standard deviation (σ) of d and h were derived from nominal values (i.e., d=19 mm and h=100 mm) and limit tolerance ranges suggested by (Hicks 2017). The μ of f_u was assumed to be 500 MPa. The σ of f_u is based on a coefficient of variation of 5% (Hicks 2017). Regarding the concrete, C30 (μ=38 MPa, σ=4.86 MPa) was considered for NAC, while the μ and σ of RAC were sourced from literature (Ju et al. 2019), as shown in Table 1.

Table 1. Material properties of headed-stud connections

	d (mm)	h (mm)	f_u (MPa)	f_c (MPa)		
				NAC (C30)	RAC_50%RA[a]	RAC_100%RA[b]
Mean μ	18.8	99.5	500	38	37.7	33.4
Std. σ	0.24	0.91	25	4.86	6.0	6.4

Following the distributions of the basic variables, fifty thousand (n=5×10^4) samples were determined by Monte Carlo simulations (MCS). Their resistance was calculated with the PCE model and is presented in histograms in Section 3.

3. RESULTS AND DISCUSSION

Statistical evaluations of models. First, the coefficient of correlation (ρ) between the test data and PCE model predicted data was calculated to be 0.95 (Figure 1 a), indicating a sufficient correlation between them. The same evaluation procedure was performed for the calculation models in EN 1994-1-1 (2004) and Konrad (2011). Their correlations with test data (ρ=0.87 and 0.89, respectively) are not as strong as that of the PCE surrogate model (Figure 1). Furthermore, model uncertainty was evaluated by determining the statistic of bias factors (a random variable), as shown in Eq. (3).

$$\boldsymbol{\lambda} = \frac{Test\ result}{Model\ prediction} \quad (3)$$

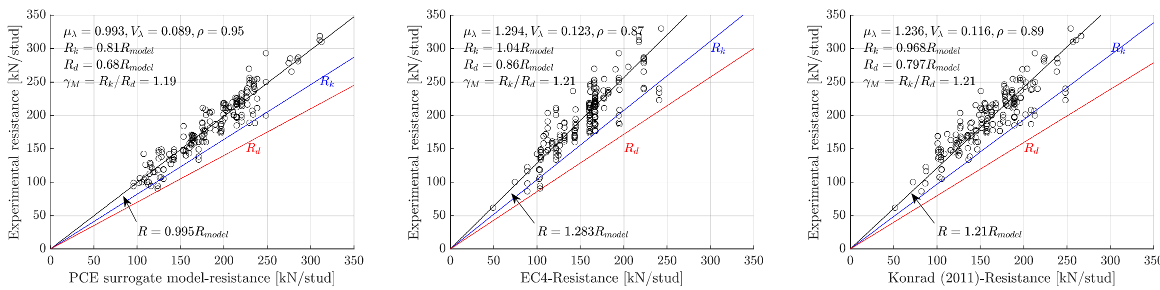
The mean values of the bias factors (μ_λ) of PCE surrogate, EC4 and Konrad models are 0.993, 1.294, and 1.236, respectively. It means that the predictions of PCE model are closer than those of the other

[a] The water-to-cement ratio is in a range of 0.38 ~ 0.71 (Ju et al. 2019).
[b] The water-to-cement ratio is in a range of 0.35 ~ 0.81 (Ju et al. 2019).

two models to the actual test results. And the coefficients of variation of the bias factors (V_λ) of the respective three models are 8.9%, 12.3%, and 11.6%, showing that the PCE model has more consistent predictions or smaller uncertainty.

To ensure structural reliability for the ultimate limit state, the designed resistance (R_d) of a structural member is defined at a 0.1% fractile of the resistance distributions. In practice, engineers usually do not know the resistance distribution and they calculate characteristic resistance (R_k) deterministically with characteristic values of material properties regulated by standards. The term R_k corresponds to a failure probability of lower than 5%. Meanwhile, standards also give a partial safety factor (γ_M) to calculate R_d, i.e., $R_d = R_k / \gamma_M$.

In turn, to propose a γ_M for the PCE model, the authors calculated R_d and R_k with the probabilistic method recommended by EN 1990 (2002), as shown in Figure 1. As a result, γ_M for the PCE model (1.19) is like that for the other two models (1.21). Overall, the PCE model delivers a slightly more economical design than the others. This can be understood in a way that for a given headed-stud connection with a test result of 1, the design resistance calculated from PCE, EC4, and Konrad models are 0.685 (=1/0.993*0.68), 0.665 (=1/1.294*0.86), and 0.645 (=1/1.236*0.797), respectively. Thus, to achieve the same resistance, the design using the PCE model is more economical.

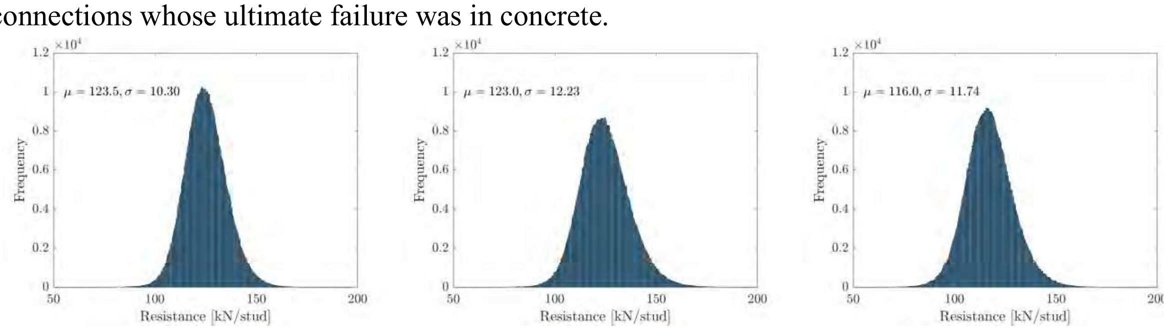


(a) PCE surrogate model (b) EN 1994-1-1 (2004) model (c) Konrad (2011) model

Figure 1. Statistical determinations of PCE surrogate model and existing mechanical models

Statistical analysis of headed-stud RAC resistance using PCE model. As the μ of RAC_50%RA is similar to μ of NAC and σ of the former is larger than the latter, the mean resistance of headed-stud connections using RAC_50%RA is not compromised (123.5 vs. 123.0 kN/stud) but the standard deviation is a bit higher compared with its counterpart (i.e., 12.23 vs. 10.30 kN/stud), as shown in Figure 2. When using RAC_100%RA instead of NAC, the mean resistance decreases slightly from 123.0 to 116.0 kN/stud and the standard deviation increases slightly from 10.30 to 11.74 kN/stud. However, the compressive strength of RAC_100%RA can be improved in many ways, e.g., by reducing water-to-cement ratio. It is promising that headed-stud connections using RAC_100%RA can achieve the same reliability as headed-stud connections with commonly-used NAC C30.

It should be noted that the above finding is drawn from the stud-failure controlled designs. Further studies are needed to address the effects of using RAC on resistance uncertainty of headed-stud connections whose ultimate failure was in concrete.



(a) NAC (b) RAC_50%RA (c) RAC_100%RA

Figure 2. Resistance distributions of NAC and RAC headed-stud connections (n=50000)

4. CONCLUSION

The study illustrated the feasibility of using PEC to predict the resistance of headed-stud connections in solid slabs with the relevant independent random variables. The PCE surrogate model has smaller uncertainty than the conventional mechanical models in EN 1994-1-1 and Konrad (2011). Besides, given a target resistance, the PCE model leads to slightly more economical design. It is expected that the uncertainty of PCE model will be further reduced, provided that the experimental design covers at best the domain of variation of the parameters. Considering these remarkable advantages, the authors propose to use data-driven PCE surrogate model for design of structural members and for quantifying the resistance reliability (uncertainty) of structural members using RAC.

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