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Assessment of Sufficient Number of Samples for Full-Scale Test of Hollow-Core Slabs



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ABSTRACT

Structural reliability of hollow-core slabs is critical in both new construction and reuse-oriented projects. Load testing is a central verification method, though its purpose differs between these contexts. In new construction, quality control is primarily based on material testing, with load testing serving as a voluntary method to confirm product consistency and the applicability of the resistance model used. In reuse-oriented projects, however, load testing becomes essential because material properties cannot be altered, and quality assurance relies on existing information and test results from a finite population of slabs.

This study identifies the statistical uncertainty associated with the number of samples in HCS shear testing, using 188 full-scale test results from the literature and from this research. The results show substantial variation even among slabs with identical design parameters, and no correlation between variability and production year, slab height, concrete compressive strength, or strand cover depth was found. Increasing the number of samples significantly improves the estimated characteristic resistance value, while finite-population effects remain minor except in very small populations. The findings highlight the need to account for statistical considerations when making preliminary decisions about the required number of samples.

Key words: Hollow-Core Slab, Load Test, Number of Samples, Shear Resistance, Acceptance Criteria.

1. INTRODUCTION

Ensuring the structural reliability of Hollow-Core Slabs (HCS) is a fundamental concern in both new construction and reuse-oriented projects. Among the available quality control measures, load testing plays a pivotal role in verifying performance and safety. In new manufacturing operations, regular monitoring of production processes is required to ensure compliance with technical and safety standards. The primary purpose of load testing in this context is to confirm product consistency and validate structural capacity.

The requirements for HCSs in new production are typically governed by national standards. However, according to the European standard EN 13369:2023 [1], the structural integrity of precast concrete elements can be demonstrated through continuous quality control of the constituent materials. Under this, load testing is not mandatory but may serve as a substitute for other verification methods, such as compressive strength testing, particularly in assessments related to load-bearing capacity.

The relevance of load testing has grown significantly with the increasing prevalence of reuse-oriented construction projects, where existing HCS elements are reclaimed from buildings and repurposed. In such cases, material properties are fixed and cannot be modified, shifting the focus of load testing from production monitoring to the validation of structural performance in a finite population of slabs.

Within reuse projects, two distinct load testing objectives can be identified [2]:

1. Determining the characteristic value of structural capacity.
2. Verifying the known structural capacity.

In structural engineering, the characteristic value is defined as a statistical lower bound, chosen so that only a defined portion of the population is expected to fall below it. For the structural capacity, it is determined either from characteristic material properties or directly from load-test results. In structural engineering the characteristic value for concrete structures is typically taken as the 0.05-quantile, meaning that 95% of the population are expected to exceed this value [3]. This choice is conventional, which means other statistical bounds could be used. The characteristic value thus represents a conservative estimate of capacity and serves as the basis for verifying that the majority of HCSs meet the required value.

The latter, verification of known capacity, is closely related to quality control practices in new production, where load testing is used to confirm the reliability of the design model and known characteristic material properties under predefined conditions. In contrast, determining the characteristic value for structural capacity through testing requires inferring material properties from test results, as they are not known in advance. This approach is typically employed when the structural capacity cannot be calculated from known information. However, if the structural capacity can be calculated and the characteristic material properties are known based on archive study, such as original design documents or construction records, then testing serves primarily to verify those calculations as in new production. Conversely, when no characteristic material properties can be retrieved and the structural capacity of a finite population is the objective, the characteristic value for structural capacity can be derived directly from load testing. In this scenario, the number of samples must be sufficiently large to ensure reliable estimation of structural adequacy across the population of slabs intended for reuse.

The sufficient number of samples is intrinsically linked to the variability in slab characteristics, including geometric dimensions, concrete compressive strength, prestressing strand properties, initial prestress levels, and associated prestress losses [4, 5, 6]. It is self-evident that greater variability increases statistical uncertainty, necessitating a larger number of samples to achieve confidence in the estimated design value [7]. However, a smaller number of samples may be acceptable, provided the results meet the statistical uncertainty in the interpretation of the results, which leads to a higher reduction in the determined characteristic value. Previous studies have studied the correlation between predicted and observed shear and bending resistance [4, 8, 9] with a lack of explicit consideration of the statistical uncertainty in variance, i.e. number of samples, and Acceptance Criteria (AC). Without considering these, the estimation of resistance can lead to overconfidence in model applicability across diverse HCS population.

Another key distinction between the two objectives lies in the current methods in interpretation of test results. When determining the characteristic value for structural capacity, general statistical methods are employed to derive a value based on population-level inference from a sufficiently large number of samples, which is not widely used for virgin or reclaimed HCSs. In contrast, verification of calculated capacity currently relies on individual test outcomes or the mean value derived from a small number of samples and is not therefore considering other untested HCSs in the population [10, 11]. The test results are typically compared to calculated resistance, when it is about validation of the used resistance model. However, this might include risks in overestimations of the actual characteristic resistance, as the small number of samples can be non-representative and the prediction error can be significantly incorrect.

The primary objective of this study is to quantify the statistical uncertainty associated with number of samples in load testing of HCS. Building on this analysis, the scope of the study is threefold:

1. To determine probable distribution of variation in HCS shear resistance from existing full-scale test results,
2. To determine the possibility of evaluating variation in shear resistance from variation of other characteristics,
3. To determine the effect of increasing number of samples on the prediction error and finite population.

The next part of the study examines the factors affecting to the variation in the shear resistance found in literature and the requirements for the full-scale test of HCSs currently applied in practice. The third section presents the dataset and analytical methods used in the research. The final part outlines the results and offers a critical evaluation of the findings to achieve the scope of this study.

2. SHEAR RESISTANCE TEST ON HOLLOW-CORE SLABS

2.1 Variation in shear resistance

The reliability of resistance models in structural design depends on the variability observed in measured resistances. Higher variability increases the need for larger numbers of samples and careful interpretation to ensure statistically sufficient characteristic resistance. These uncertainties also influence the AC used to verify predicted resistance values and shape the overall safety margin.

For HCSs, resistance prediction is particularly sensitive to geometric and material parameters. Fan et al. [12] identified slab depth and gross concrete area as the most influential parameters with prestress force, strand cover depth and web thickness. These findings align with earlier studies highlighting the role of geometric characteristics such as height and void shape in brittle web-shear failures [8, 14, 15]. Such sensitivities have reduced the reliability of existing models, prompting more conservative design approaches in standards [10, 16, 17].

Model reliability also depends on the failure mode, as the location of the first crack affects the final mechanism (Figure 1). Additional failures may arise from insufficient anchorage length. Despite these uncertainties, Kim et al. [9] showed that flexural resistance predictions in ACI 318-19 [16] and the PCI Design Handbook [17] remain conservative. Fan et al. [12] further proved that the ACI 318-19 [16] shear resistance model performs more accurately for HCSs with depths below 318 mm than for deeper units. In EN 1168:2005 + A3:2011 [10] the model uncertainty has led to a reduction in the overall resistance regardless of geometry with a reduction factor. These results indicate that shear resistance reliability varies significantly across HCS geometries.

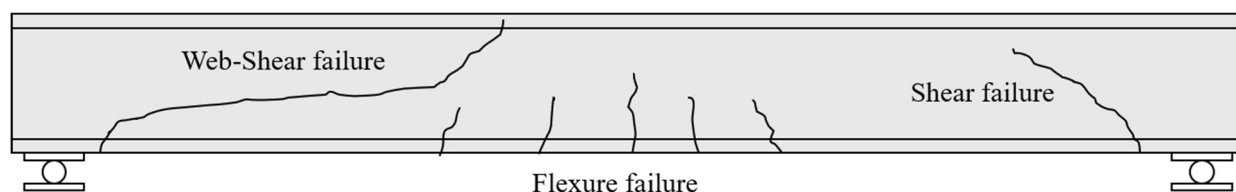


Figure 1 – The most typical failure modes of HCSs.

Material variability is another key factor. Thienpont et al. [13] showed that variability in concrete tensile strength strongly affects measured shear resistance. This emphasizes the importance of

characteristic values in design and the role of quality control in ensuring products exceed these values. Thus, uncertainties arise not only from geometry but also from material properties.

Modelling uncertainties have also been widely recognised. Sarkis et al. [4] showed that shear resistance predictions are sensitive to several shear-span-dependent parameters, with different factors domination at short and long spans. For prestressing-related uncertainties, Brunesi et al. [8] found that while the assumed prestress distribution shape has little influence, variations in prestress losses and effective bond length can noticeably affect predicted resistance. Together, these findings highlight that modelling assumptions and prestressing behaviour show additional variability that must be considered when interpreting test results.

A further source of uncertainty, rarely considered in the literature, is the test setup itself. Although standardised procedures reduce these effects, minor uncertainties in equipment and boundary conditions remain.

In conclusion, previous studies show that uncertainties in geometry, material properties, modelling assumptions, and prestressing behaviour all contribute to the variability observed in full-scale tests. However, the interpretation of this variability and the determination of sufficient sampling in quality assurance have received limited attention. This highlights the need to evaluate the overall probability of variability and its effect on sampling requirements, providing a basis for selecting an appropriate preliminary number of samples for load testing of HCSs.

2.2 Acceptance criteria and number of samples for shear resistance test

In the quality assurance process, products must meet the predetermined AC that are used to regulate uncertainties in production. The AC is typically defined so that the safety of the products is ensured, and the criteria vary for different properties as well as internationally. Current AC for load testing of HCSs are outlined in EN 1168:2005 + A3:2011 [10] and the Norwegian standard NS 3382:2019 [11], which specifically addresses the reuse of HCSs. While both standards base AC on the ratio between tested resistance F_{TEST} and calculated resistance F_{CALC} , NS 3382:2019 requires substantially stricter criteria and higher number of samples for reclaimed HCSs, see Table 1. The calculated resistance in both standards is obtained using the same resistance model of EN 1168:2005 + A3:2011 [10], thus the AC being dependent on the uncertainty of the resistance model:

$$V_{Rdc} = \varphi \frac{I b_w}{S} \sqrt{f_{ctd}^2 + \beta \alpha_l \sigma_{cp} f_{ctd}}, \quad (1)$$

where φ is a reducing factor, I is the second moment of area, S is the first moment of area above and about the central axis, b_w is the width of the cross section at the centroidal axis, f_{ctd} is the design value of tensile strength of concrete, β is a reducing factor for transmission length, α_l is the degree of prestressing transmission, and σ_{cp} is the full concrete compressive stress at the centroidal axis. It is also worth noting that the model in EN 1168:2005 + A3:2011 [10] may have been modified at the national level.

Although both standards specify AC for mean and individual test results, the fixed AC do not consider the statistical properties of the tested population and untested HCSs. This means that applying it to all HCSs, the variability is ignored, i.e. assumed to be constant, and that the resistance model is equally accurate for all HCS types with different parameters. However, in

practice neither of these assumptions are true. Several factors affecting the variation in shear resistance test were identified from the literature in the previous section, leading to inconsistent prediction error and risk in population estimation. In addition, the inconsistency is increased by the known model uncertainty from several studies, where one of the major underestimations is brittle web-shear failure in deep slabs [8, 14, 15], making the resistance model more conservative for shallow slabs and increasing the risk of rejection.

In this sense, Pajari and Makkonen [18] proposed that quality control of new production should instead rely on quantiles determined directly from test results, allowing the desired acceptance probability and quantile to be selected on a case-by-case basis. Applying this approach to reuse projects and HCSs is, in the authors' view, preferable to compare mean test values with calculated characteristic resistances as required by current standards. Calculating the characteristic value directly from test results allows the favourable resistance of shallow HCSs to be more effectively utilized by reducing both over- and underestimation of the resistance.

One way to determine characteristic resistance based on the test results is using Prediction Interval (PI), where the importance of variability becomes clear:

$$PI = \bar{x} \pm t_{n-1}^{-1} \cdot s \sqrt{1 + 1/n}, \quad (2)$$

where $\bar{x}$ is mean value, t_{n-1}^{-1} is critical value for the t-distribution, s is sample standard deviation, and n is the number of samples. In the PI the prediction error depends on both the standard deviation and the number of samples, as the variance of the prediction error is:

$$V(\bar{x} - x_{n+1}) = V(\bar{x}) + V(x_{n+1}) = s^2/n + s^2 = s^2[1 + (1/n)], \quad (3)$$

Considering these effects in the AC, PI could therefore provide consistent reliability of the AC for different HCS with different design parameters, unlike the fixed AC.

However, the major difference in the new production and reuse-oriented projects becomes in two things: (i) characteristic material properties and (ii) population size. In new production, it is relevant to assume infinite population in quality control, but in the reuse-oriented projects the representativeness of the sampling can often be better, as the HCS population is limited within a building. Since prediction error decreases with number of samples (Eq. 3), the choice becomes an economic decision, as more samples reduce uncertainty but increase costs. This is especially relevant for small populations where the Finite Population Correction (FPC) factor (Eq. 4) can be applied.

$$FPC = \sqrt{(N - n)/(N - 1)}, \quad (4)$$

where N is the population size.

The FPC adjusts the standard error when sampling without replacement from a population that is not large compared to the number of samples. The factor reduces the estimated uncertainty because each sampled unit provides information about the remaining population. It is used to avoid overestimating variability when the sample represents a minor portion of the entire population. Although the FPC cannot be applied to the prediction error to reduce the uncertainty, it is relevant for decision-making and should be considered in reuse projects where populations can often be small and the number of samples tends to close the population size.

When considering characteristic material properties, the key difference between new production with virgin HCSs and reclaimed HCSs lies in how the characteristic value is determined. In new production, the characteristic value is based on quality control of the materials used during manufacturing [1]. In practice, quality control aims to ensure that the produced elements consistently exceed the characteristic value, rather than merely meet it. As a result, the actual performance level of the population often lies well above the theoretical characteristic limit. Statistically, the characteristic value corresponds to the minimum quantile of the estimated population distribution, even though the true population may perform significantly better. In theory, for example the 0.05-quantile in Eurocode 2 [3] should be exceeded by 95% of the products, but in production the proportion exceeding this level can be typically much higher.

For reclaimed HCSs, the situation is similar when the characteristic values are known from existing documents. However, in a scenario where the characteristic values are not known and must be determined by testing, the characteristic value is based on the distribution properties of the samples. In this case, the corresponding probability is chosen directly, with the 0.05-quantile used in Eurocode 2 for the material properties of concrete structures [3]. As a result, the tested characteristic value may be higher than that in new production, implying higher risk of individual products falling below characteristic value, compared to the current quality assurance procedure used in new production.

Table 1 – Currently applied requirements for load testing of HCSs in standards and guidelines.

Standard	Requirement for number of samples	Acceptance criteria ^{a)}
EN 1168:2005 + A3:2011 [10]	-	$F_{\text{TEST}}/F_{\text{CALC}} \geq 0.95$, for individual test result $F_{\text{TEST,M}}/F_{\text{CALC}} \geq 1.0$, for $n = 3$
NS 3382:2019 [11]	3 or 1/50, whichever is greater	$F_{\text{TEST,M}}/F_{\text{CALC}} \geq 1.25$, when $n < 6$ $F_{\text{TEST,M}}/F_{\text{CALC}} \geq 1.10$, when $n \geq 6$
ACI 318-19 [16]	-	No fixed acceptance criteria
PCI handbook [17]	Recommendation of at least 3 specimens	No fixed acceptance criteria

^{a)} $F_{\text{TEST,M}}$ = mean value of test results.

3. RESEARCH MATERIAL AND METHOD

3.1 Data

The research material consists of 188 full-scale test results collected from 13 publications [12, 14, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29], including six HCS shear test results from this study. All failure mechanisms are included in the data to consider the probability of different failure types. Each HCS type with identical design parameters, including geometry, concrete properties, number and prestress levels of strands and test setup, was separated and considered as their own HCS type. The separation resulted in groups containing two to eight slabs, with most groups containing two or three slabs. While the size of the same HCS types provide an approximation of the variation, this reflects the general lack of repeated testing on identical HCS types in the available literature. Consequently, the estimated CoV may be either over- or underestimated, introducing

uncertainty into the assessment of population-level variability. To mitigate this limitation in the data, simulations were performed to supplement the limited number of tested HCSs (see Section 3.2)

The HCSs tested in this study were produced in 1984 and later reclaimed and tested in 2023. The geometry of the slabs is shown in Figure 2. The shear resistance test was performed according to SFS-EN 1168:2005 + A3:2011 [10]. Other parameters of the HCSs are presented in Table 2. Table 3 presents the references and variability of the parameters of each HCS type.

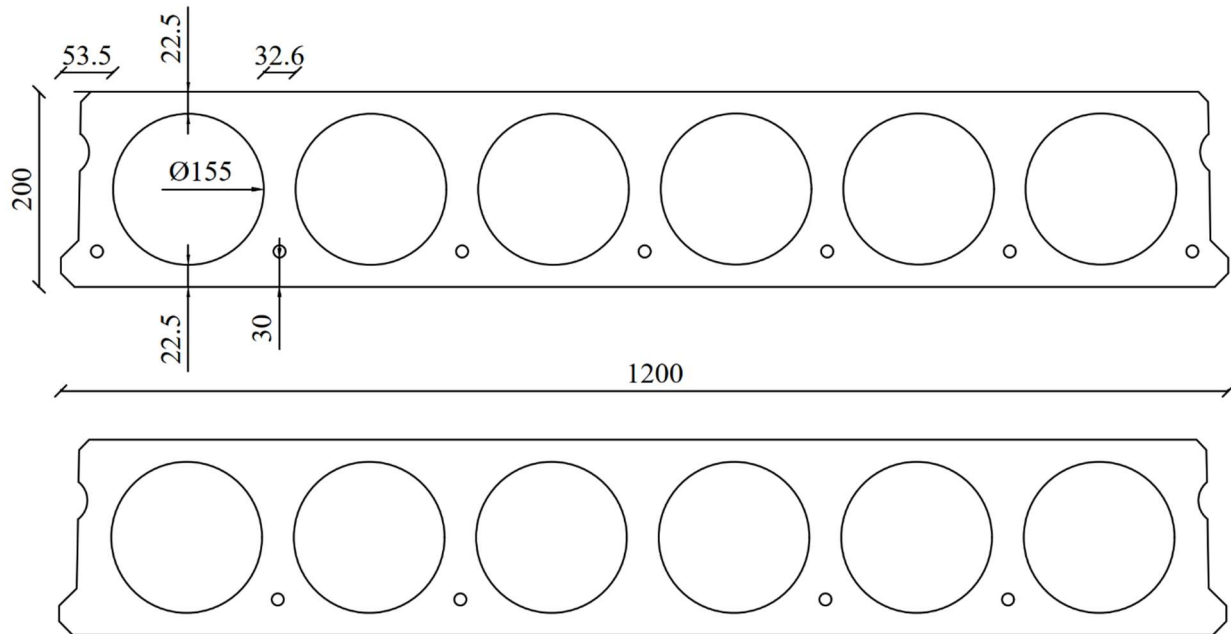


Figure 2 – Geometry of the tested HCSs in this study (HCS type 72 above and HCS type 73 below), dimensions are the same for both types and given in mm.

Table 2 – Parameters of tested HCSs in this study.

Specimen (HCS type number)	Sample	Strand diameter (number of strands)	Designed prestress level [MN/mm ²]	Compressive strength of concrete [MPa] ^a	Ultimate load [kN]
P20-4X (72)	1	12.5 mm (4)	900	79.2	89
	2	12.5 mm (4)	900	76.8	86
	3	12.5 mm (4)	900	79.9	103
P20-7X (73)	1	12.5 mm (7)	900	75.5	126
	2	12.5 mm (7)	900	75.9	168
	3	12.5 mm (7)	900	77.2	141

^a An average of 3 core samples with a diameter of 50 mm.

Table 3 – Initial data of the research material from literature and this study.

Reference	HCS type number	Production year (year of testing)	Height [mm]	Number of slabs	CoV of resistance	CoV of compressive strength	CoV of cover depth of strands
[14]	1	1999 (1999)	265	2	0.9	0.4	10.1
	2	1991 (1991)	265	2	2.8	-	-
	3	1993 (1993)	265	3	4.4	2.9	4.3
	4	1993 (1993)	265	3	10.5	2.9	4.3

[19]	5	1994 (1994)	265	2	0.5	-	1.8
	6	1998 (1998)	320	2	0.8	-	1.7
	7	2003 (2003)	320	2	9.7	0.5	1.8
	8	1999 (2000)	400	2	8.3	-	-
	9	2011 (2011)	406.4	4	17.3	-	-
	10	2011 (2011)	406.4	2	1.4	-	-
	11	2011 (2011)	406.4	2	4.0	-	-
	12	2011 (2011)	508	2	8.9	-	-
	13	2011 (2011)	406.4	2	16.1	-	-
	14	2011 (2011)	406.4	4	9.3	-	5.7
	15	2011 (2011)	406.4	4	26.0	-	0.3
	16	2011 (2011)	304.8	2	2.8	-	-
	17	2011 (2011)	304.8	2	26.9	-	5.2
[20]	18	2017 ^b (-)	406.4	8	15.6	-	-
[21] ^a From	19	2019 (-)	200	2	19.3	2.5	-
[12]	20	2019 (-)	320	2	8.0	6.7	-
[22]	21	2019 (-)	400	3	8.7	7.9	-
	22	2019 (-)	500	2	2.7	1.7	-
	23	2019 (-)	200	2	5.2	1.2	-
	24	2019 (-)	320	2	14.9	4.0	-
	25	2019 (-)	400	3	8.4	8.1	1.8
	26	2019 (-)	250	2	9.3	34.8	-
	27	2019 (-)	300	2	10.7	7.9	-
	28	2019 (-)	470	2	4.9	0.5	-
	29	2017 ^b (-)	200	2	53.0	-	-
	30	2017 ^b (-)	265	2	40.4	-	-
	31	2017 ^b (-)	400	3	0.0	-	-
	32	2017 ^b (-)	500	3	0.0	-	-
	33	2021 (2021)	200	2	0.9	-	-
[23]	34	2021 (2021)	200	2	3.5	-	-
[24]	35	2021 (2021)	200	3	18.5	-	-
	36	2018 (2018)	300	2	1.2	0.4	-
[25] ^a From	37	2018 (2018)	470	2	3.5	8.0	-
	38	2005 (-)	255	3	2.2	-	-
[12]	39	2005 (-)	320	3	4.6	-	-
[26]	40	2005 (-)	400	3	2.7	-	-
	41	2005 (-)	265	3	8.8	-	-
	42	2005 (-)	320	3	5.7	-	-
	43	2005 (-)	260	3	5.1	-	-
	44	2005 (-)	320	3	1.1	-	-
	45	2005 (-)	260	3	2.6	-	-
	46	2005 (-)	320	3	1.9	-	-
	47	2005 (-)	400	3	1.0	-	-
	48	2005 (-)	260	3	1.1	-	-
	49	2005 (-)	320	3	9.2	-	-
	50	2005 (-)	400	3	5.0	-	-
	51	2021 (2021)	304.8	2	11.6	-	-
	52	2021 (2021)	304.8	2	2.0	-	-
	53	2021 (2021)	304.8	2	1.1	0.6	-
	54	2021 (2021)	304.8	2	0.6	2.6	-
	55	2021 (2021)	304.8	2	8.2	1.1	-
	56	2021 (2021)	304.8	2	6.7	0.6	-

	57	2021 (2021)	304.8	2	11.6	2.3	-
[27]	58	2020 (2020)	400	2	4.1	-	-
[28]	59	2020 (2020)	265	3	3.7	-	-
	60	2020 (2020)	320	3	4.2	-	-
	61	2020 (2020)	400	3	3.7	-	-
[29]	62	1985 (1985)	203.2	3	14.2	-	-
	63	1985 (1985)	203.2	2	6.0	-	-
	64	1985 (1985)	203.2	4	10.9	-	-
	65	1985 (1985)	203.2	3	34.0	-	-
	66	1985 (1985)	203.2	3	10.2	-	-
	67	1985 (1985)	254	2	15.2	-	-
	68	1985 (1985)	254	2	1.4	-	-
	69	1985 (1985)	254	2	1.8	-	-
	70	1985 (1985)	254	2	2.4	-	-
	71	1985 (1985)	254	2	13.1	-	-
This study	72	1984 (2023)	200	3	9.8	2.1	20.4
	73	1984 (2023)	200	3	14.7	1.2	1.1

^a Original publication was not available.

^b A year of submitted publication.

(-) Unknown.

3.2 Statistical analysis and simulation procedure

Variation in shear resistance test results

The variation in full-scale test of HCSs was analysed for all HCS types collectively to estimate the statistical distribution of possible variation within a single population. The analysis of the distribution was conducted both with the original data as they are and simulated data based on the original data. A set of 10.000 simulated test results were generated using a bootstrap simulation, in which the samples are repeatedly drawn with replacement from the original dataset. The simulated dataset was then used to further assess the statistical distribution of variation in resistance values. The simulation was to compensate for the limited number of samples for each individual HCS type from literature, thereby enabling a more reliable estimation of the underlying population of the CoV.

To determine the most suitable distribution for each HCS type, the Kolmogorov-Smirnov (KS) test was applied. The following distribution types were considered: normal, log-normal, gamma, beta, and Weibull distributions.

Correlation between variations in design parameters and shear resistance test

From the original data, the production year, HCS height, concrete compressive strength and cover depth of strands were individually analysed to assess the correlation to variation in resistance. Only HCS types with measurable variation in concrete compressive strength, cover depth of strands, and resistance were included in the analysis, except for production year and height, which were evaluated for each available HCS type. If production year was not reported, the year of submitted or published publication was used. If several results for compressive strength and cover depth of strands were reported for an individual HCS, an average value was used for that sample.

Sufficient number of samples for shear resistance test

To evaluate how the number of samples affects the characteristic resistance value with different variations, the variation in the 0.025-quantile, mean value, and 0.975-quantile from the simulated

distribution were analysed. The prediction error of Eq. 2 was calculated for each number of samples from 2 to 200. For comparison, the effect of a coverage estimator (Eq. 5) was also analysed, as it is commonly used in the AC of quality assurance procedures. The coverage estimator was found to provide a higher acceptance probability than the prediction estimator when fewer than four samples were available, while exhibiting a similar overall behaviour to the prediction estimator [18].

$$k_n^{cov}(p, \alpha) = -t_{n-1, c}^{-1}(\alpha)/\sqrt{n}, \quad (5)$$

where p is the quantile of the standard normal distribution, α is the confidence level of the noncentral t-distribution, and c is the non-centrality parameter in Eq. 6.

$$c = -\phi^{-1}(p)\sqrt{n}, \quad (6)$$

Both the prediction error and coverage estimator were calculated with the 0.05-quantile. In the coverage estimator also 75% confidence level was used, as it is recommended by ISO 12491:1997 [30], and it is close to prediction error with 0.05-quantile [18]. Additionally, the effects of both were determined in relation to the mean value.

To consider the limited number of HCSs within a building, the influence of the FPC factor in the SEM was evaluated for each chosen variation and number of samples. In addition, the SEM was analysed with an assumption of infinite population, representing a quality control procedure of virgin products. The influences were determined in relation to the mean value.

4. RESULTS AND DISCUSSION

4.1 Variation in shear resistance test results

Figures 3 and 4 present the histogram for the non-simulated data and the data-driven simulations. For the non-simulated dataset, the coefficient of variation (CoV) ranges from 0% to 53%, with a mean of 8.5%. For the simulated dataset, the corresponding range is 0% to 114%, with a mean of 9.4%. Based on the KS test, both datasets follow a Beta distribution. The wide range of CoV values indicates that the variability in HCS resistance can differ significantly, implying that the representative number of samples for reliable resistance estimation may vary depending on the potential magnitude of the CoV.

However, inspection of the lower tail in Figures 3 and 4 shows that most HCS types exhibit low CoV values. Figure 4 further points out that 95% of the simulated CoVs fall between 0.13% and 37.4%, and that 50% of the simulated values are below 9.4%. These results indicate generally uniform production quality of HCSs and suggest that, in most cases, the studied HCS type is relatively homogeneous.

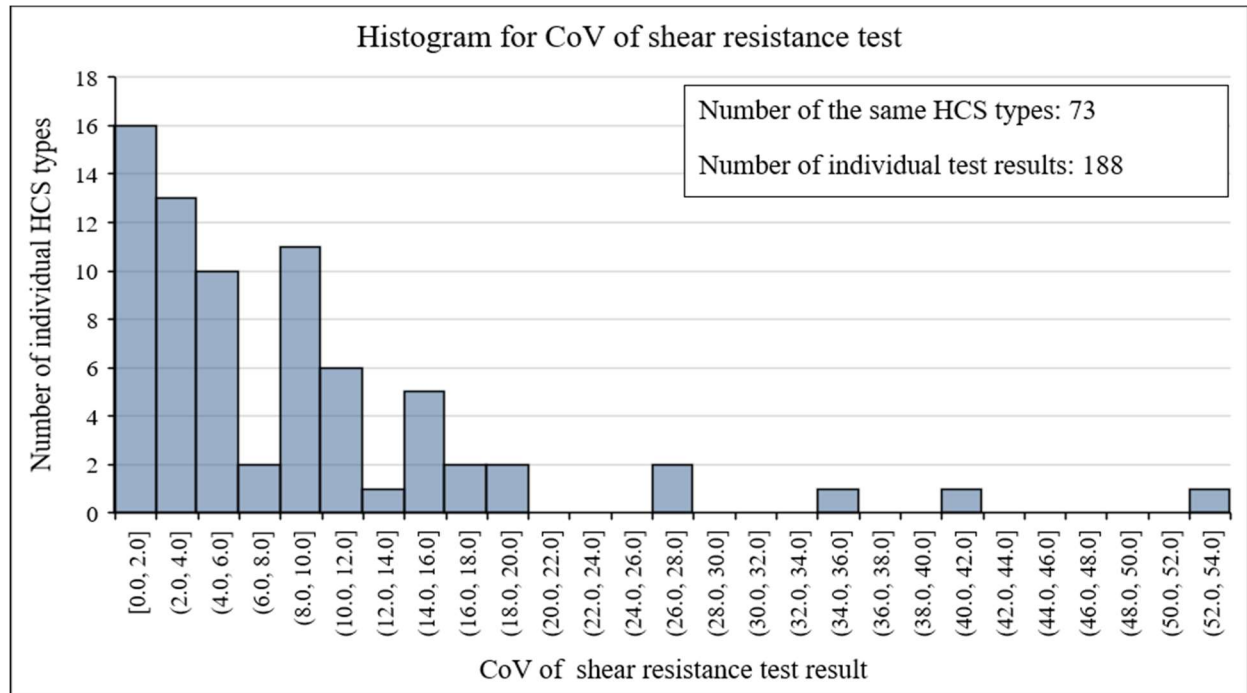


Figure 3 – Histogram for CoV of shear resistance test results from literature and this study.

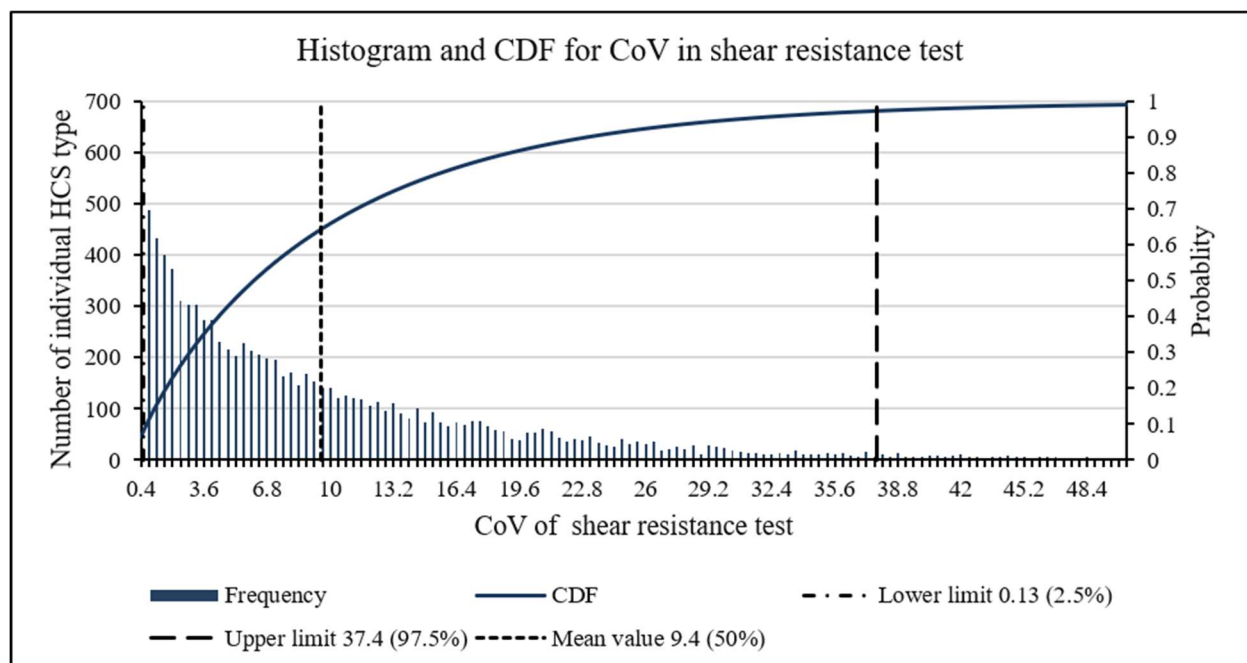


Figure 4 – Histogram for simulated CoV of shear resistance test results from literature and this study.

Table 4 – KS-test results for how various distributions fit to the simulated data.

Distribution	Simulated values (n = 10000)		Data values (n = 73)	
	D-value	p-value	D-value	p-value
Normal	0.1738	0.0000	0.1785	0.0177
Log-normal	0.0492	0.0000	0.5317	0.0000
Weibull	0.0140	0.0404	0.0900	0.5731
Gamma	0.0252	0.0000	0.2085	0.0032
Beta	0.0087	0.4334	0.0668	0.8833

4.2 Correlation between variations in design parameters and shear resistance test

Production year

Figure 5 presents the production year of HCSs from data in relation to the CoV of resistance. The results show that the CoV values vary significantly for HCSs produced both in the 1980s and the 2020s, indicating no consistent correlation between production year and resistance variability. Therefore, preliminary assessment of sufficient number of samples for full-scale test cannot be done based on the production year and each production year should have the same quality assurance procedure. Notably, the dataset is concentrated on HCSs produced in the 2000s, with most of the HCSs produced between 2017 and 2021, which may indicate increased interest in brittle web-shear failure of HCSs during that period.

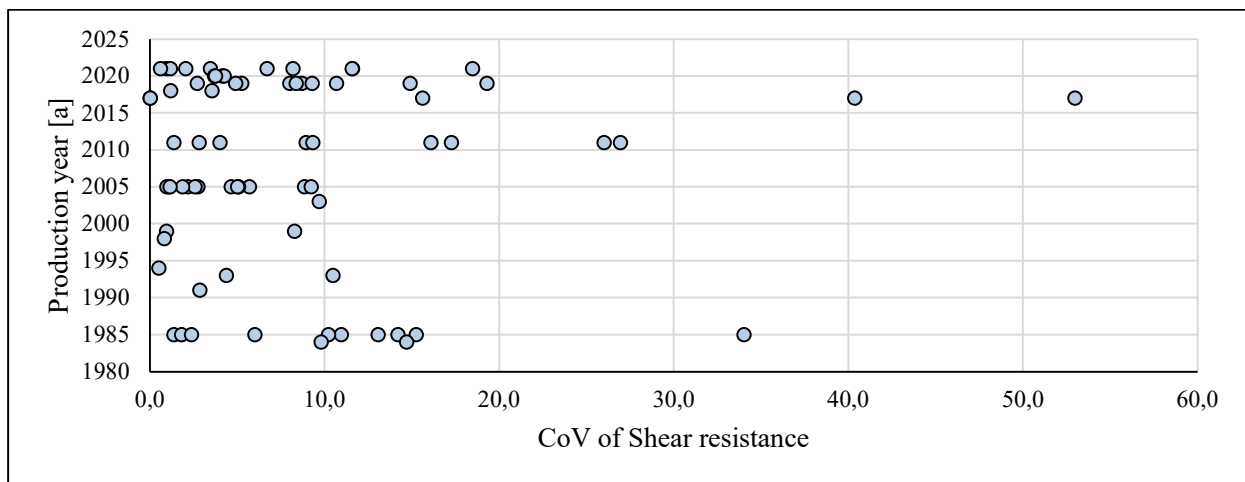


Figure 5 – Production year of HCSs in relation to CoV of shear resistance test.

Height

Figure 6 illustrates the correlation between height of HCSs and the CoV of resistance. The results indicate that there is no clear correlation, meaning that preliminary estimation of sufficient number of samples based on HCS height is not feasible. However, it should be noted that in previous studies [12] it has been found that the height is correlated with the failure mechanism and thus reliability of the current resistance models. Even if height is not correlated with the variation of the resistance, it should be considered in the resistance models, as the resistance models are more conservative for lower HCSs.

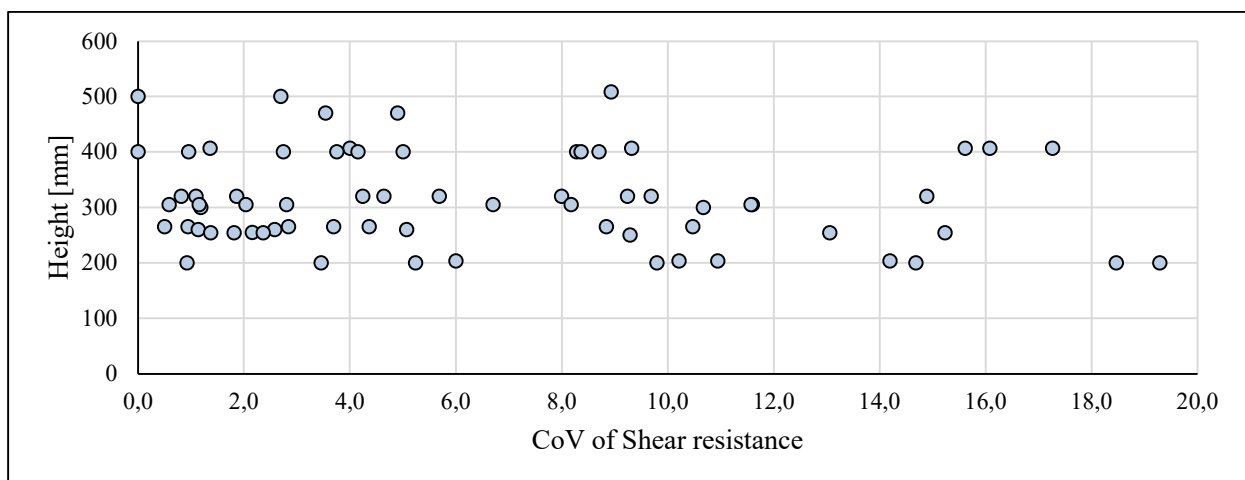


Figure 6 – Height of HCSs in relation to CoV of shear resistance test results.

Compressive strength

The correlation between the CoV of compressive strength and the CoV of resistance is presented in Figure 7. The results show that the variation in compressive strength of HCSs does not correlate with the variation in the shear resistance test results. The CoV of compressive strength ranges from ~0 to 8.1, except one outlier with the CoV of 34.8. In comparison, the corresponding range of CoV of resistance lies between 0.6 and 19.3. Based on these results, it cannot be concluded that a sufficient number of samples for full-scale test can be assessed from the variability of compressive strength in HCSs.

The results also support earlier findings regarding the variation in shear resistance tests, as there are multiple factors affecting resistance [12]. In addition, determining compressive strength with core samples involves several factors of uncertainty. Among the uncertainties, the most significant is related to sample size, as typically only very small cores samples (50 mm in diameter) can be taken from the HCSs. Such small cores have been shown to have a significant variability compared to larger diameters [31]. However, it should be noted that compressive strength of concrete is one of the most essential factors in resistance models, as the tensile strength of concrete is usually determined from the compressive strength [10, 16, 17].

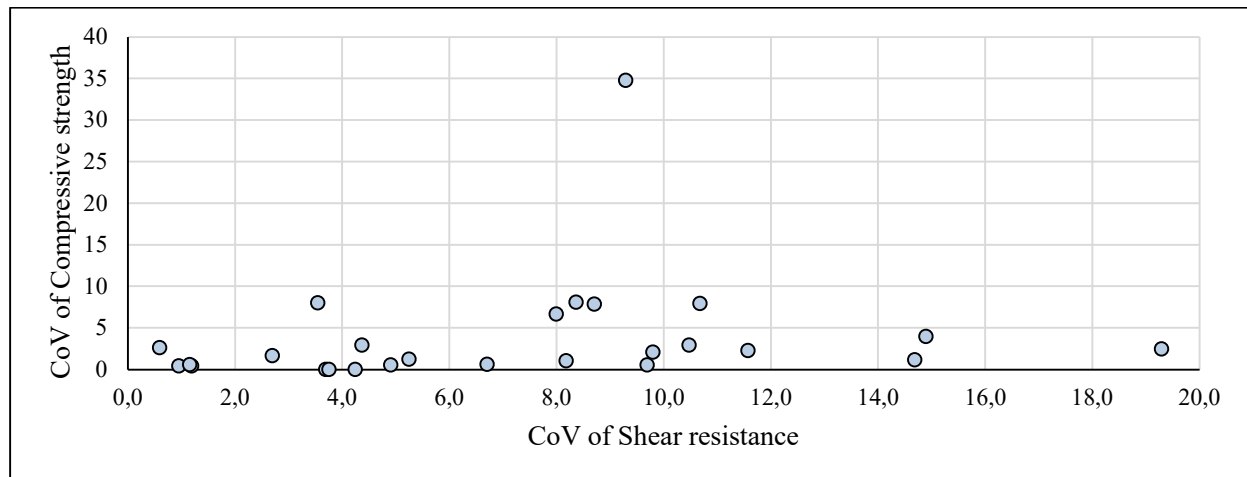


Figure 7 – CoV of compressive strength of concrete in relation to CoV of shear resistance test results.

Cover depth of strands

Figure 8 presents the correlation between the CoV of the cover depth of strands and the CoV of shear resistance test. The dataset included twelve HCS types for which the cover depth had been measured. The variation in concrete cover thickness is notably low, except for two outliers (10.1 and 20.4) without a clear reason. Low variability indicates good production quality, which is expected for HCSs, as the prestressing strands are positioned at their intended height with machinery.

However, based on the results, no clear correlation can be identified between the variation in cover depth of strands and the variation in shear resistance test. Consequently, measurements of cover depth of strands cannot be used to estimate the variability in shear resistance test for preliminary assessment of sufficient number of samples. The lack of a clear correlation also suggests that increasing the dataset is unlikely to strengthen the correlation between these variables.

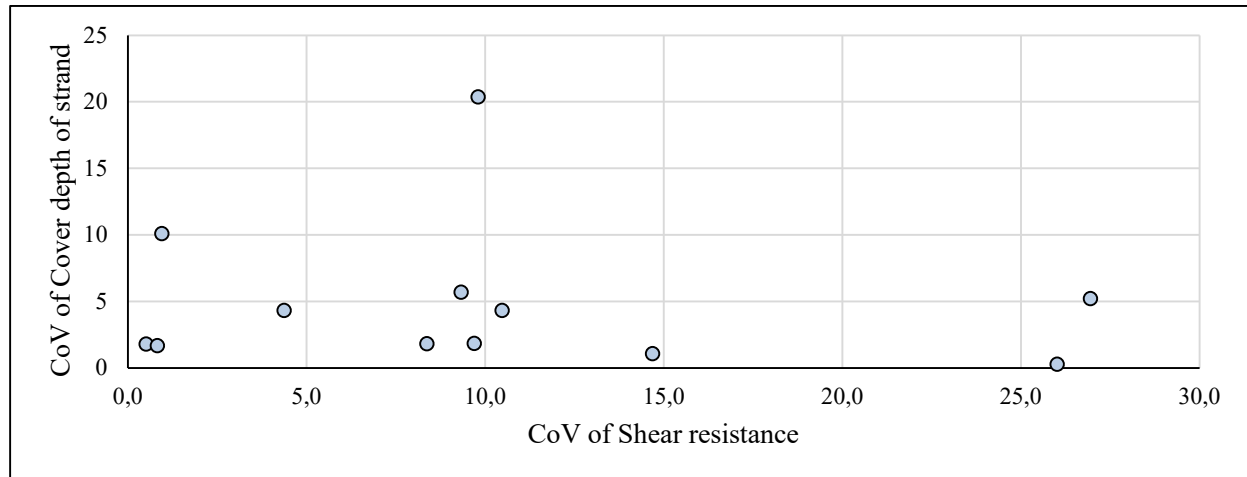


Figure 8 – CoV of cover depth of strands in relation to CoV of shear resistance test results.

4.3 Sufficient number of samples for shear resistance test

Figure 9 shows how the number of samples and the CoV influence the characteristic resistance (primary y-axis) and the Standard Error of the Mean (SEM) of a finite and infinite population (secondary y-axis). Three CoV values were examined (0.13%, 9.4%, and 37.4%), corresponding to the 95% prediction interval and the mean of the observed variation. The effect of increasing number of samples is presented in Table 5. Both estimators demonstrate that high CoV combined with a small number of samples leads to large changes in the characteristic value. For example, with a CoV of 37.4%, increasing the number of samples from two to three raise the characteristic value by nearly 80%, whereas for very small CoV the change is negligible. As the number of samples increases, the effect diminishes rapidly, and beyond six samples even the highest CoV results in only minor improvements. Based on the observed mean CoV 9.4%, four samples appear to be an efficient preliminary choice, as adding a fifth sample increases the characteristic value by less than 3%.

The influence of population size is also shown in Figure 9 through the SEM. The effect is relevant only when the number of samples is small and the population consists of fewer than ten HCSs. In such cases, the number of slabs available for reuse after testing may become too small, making extensive testing impractical. This emphasizes the importance of existing information, such as design parameters and load history, when assessing small populations. For larger populations, the influence of population size on the SEM is minor, and the selection of number of samples can focus primarily on its effect on the characteristic resistance. For CoV values up to 9.4%, the SEM remains low (≤ 0.07 of the mean), indicating a generally reliable estimation of population characteristics.

In addition, the SEM indicates the potential error in estimating the population mean for a given number of samples. The results show that, for the examined CoVs, the SEM becomes notable after four samples only in the case of the highest CoV (37.4%), which is unlikely in practice. Even then, increasing the number of samples from four to six reduces the SEM by only about 3.3 relative to the mean. It should also be noted that the uncertainty related to number of samples is inherently considered for in the determination of the characteristic value through statistical factors that depend on the chosen probability and the number of samples.

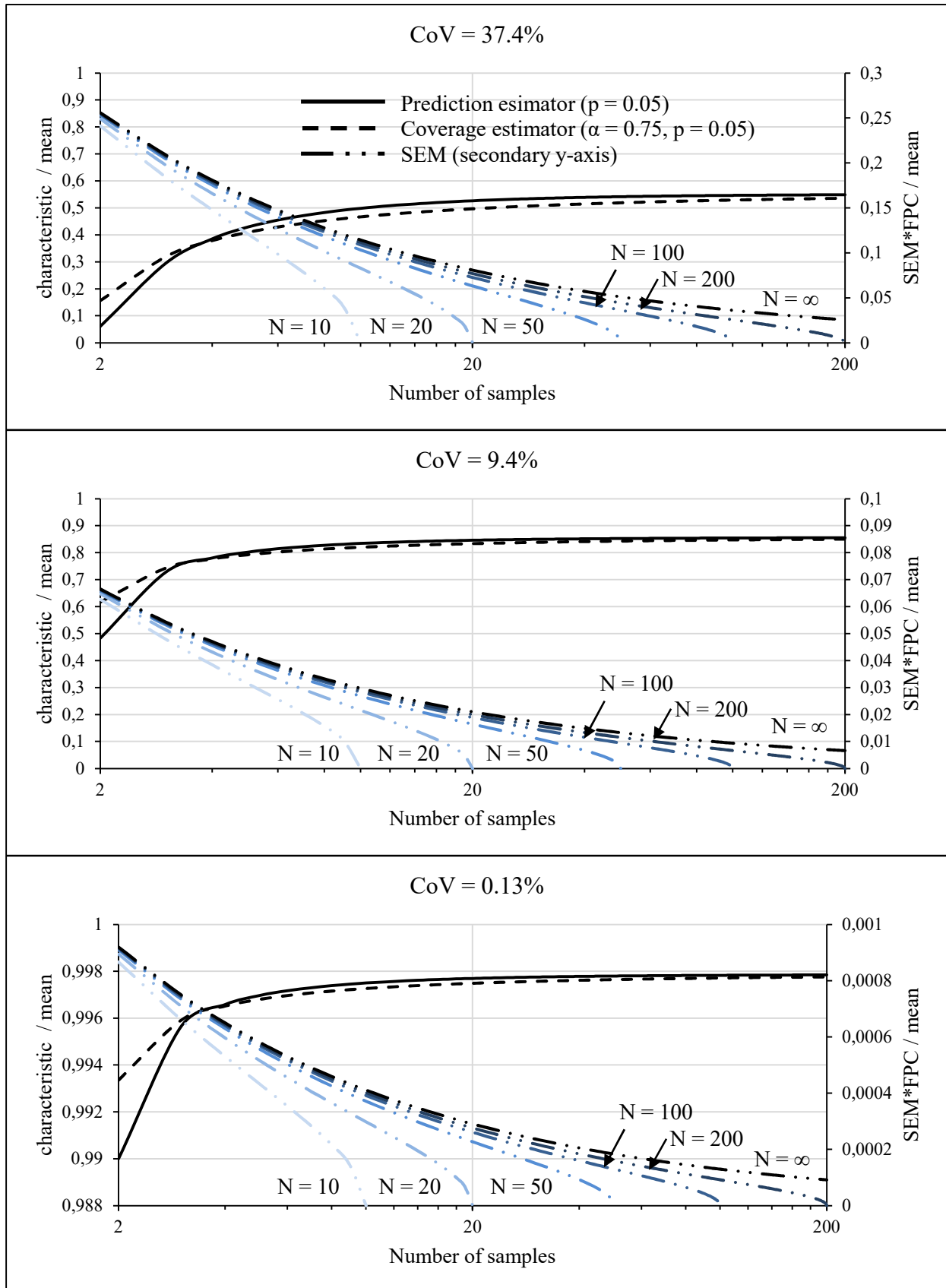


Figure 9 – Ratio of characteristic value to mean value in relation to number of samples for different CoV in shear resistance test results with prediction estimator and coverage estimator (primary y-axis). Ratio of SEM*FPC to mean value in relation to number of samples for different CoV in shear resistance test results (secondary y-axis).

Table 5 – The effect of increasing number of samples to prediction error to different CoV of shear resistance test results.

Number of samples	37.4%		9.4%		0.13%	
	Prediction	Coverage ^a	Prediction	Coverage ^a	Prediction	Coverage ^a
2 -> 3	79.4	51.0	33.7	16.9	0.56	0.26
3 -> 4	23.5	15.7	6.7	4.3	0.10	0.06
4 -> 5	10.2	7.6	2.7	2.0	0.04	0.03
5 -> 6	5.6	4.5	1.5	1.2	0.02	0.02
6 -> 7	3.5	3.0	0.93	0.80	0.01	0.01
7 -> 8	2.4	2.2	0.64	0.58	0.009	0.008

^a ($\alpha = 0.75, p = 0.05$)

5. CONCLUSIONS

This study highlights the influence of number of samples on the interpretation of shear resistance test for HCSs, as well as the effect of variability on AC. The findings demonstrate the range of variation that may occur in shear resistance test and examine whether this variation can be evaluated from production year, slab height, concrete compressive strength, or cover depth of strands. In addition, the results illustrate how different numbers of samples and variation affect the calculated characteristic resistance, and how a finite population influences the predicted characteristic value.

The results show that HCSs with identical design parameters should be treated as separate populations, as the variation in shear resistance test can differ significantly between them. This observation also supports the idea of revising current AC so that the statistical properties can be considered, rather than relying on fixed AC. Such an approach would reduce both underestimation and overestimation of characteristic resistance value.

No correlation was found between the variation in shear resistance test results and the HCSs' production year, height, concrete compressive strength, or cover depth of strands. This indicates that a sufficient number of samples cannot be preliminary estimated based on these parameters.

Increasing the number of samples from three to four can improve the characteristic resistance by approximately 24% when the CoV is high (37.4%). If the CoV is lower (9.4%), the corresponding increase in number of samples can improve the characteristic resistance value by about 7%. Thus, using four samples can be an efficient preliminary number of samples for most cases, as the mean variation in shear resistance test was found to be 9.4%. However, the effect of increasing number of samples on the characteristic value should also be considered when selecting a number of samples.

A finite population was found to have only a minor effect on small number of samples when the population consist of 20 HCSs or more. The effect becomes more significant only when the population size is 10, where the sampling fraction is large. In such cases, determining shear resistance based on existing information (design parameters, load history, etc.) becomes more relevant than conducting additional load tests. This is particularly relevant in reuse-oriented projects, where saving as many intact HCSs as possible is essential and aim.

Overall, the results underscore the importance of accounting for both slab-specific variability and sampling-related statistical uncertainty, especially when interpreting load test results from small

number of samples. These considerations are essential for determining characteristic resistance for existing HCSs for reuse.

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