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Application of the ECOV method for assessing the load-bearing capacity of existing structures

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ABSTRACT

Within circular construction, an important aspect is the assessment of existing (used) structural elements and their possibility of reuse. Nevertheless, many uncertainties must be accounted for when assessing the remaining load-bearing capacity of existing reinforced concrete elements, especially when only limited information is available. This work aims to explore a method for assessing the resistance of an existing reinforced concrete structure, accounting for uncertainties in a simplified way. This method is based on the ECOV method (Estimation of Coefficient of Variation), which provides an estimate of the variance of the structural resistance based on limited model evaluations. The procedure is illustrated by application to hypothetical reinforced concrete beams, where the assumed limit states are bending and shear. The influence of different input variables on the maximum allowable load is estimated based on the ECOV method. Different scenarios of data availability on the layout, reinforcement composition and material properties are considered.

INTRODUCTION

In circular construction, there is a significant focus on reusing existing structures or their structural elements. To evaluate the possibility of reuse, the resistance of these elements needs to be assessed. Nevertheless, when assessing the load-bearing capacity of existing structures or structural elements, there are many uncertainties, for example, due to a lack of information. Probabilistic analyses can be applied to deal with these uncertainties [1]. Distributions are assigned to different variables in the resistance models, resulting in a distribution of the load-bearing capacity. Depending on the available information, the distributions of the variables in the resistance models can be more vague or informative. This influences the final estimate of the remaining load-bearing capacity of the structure and the associated uncertainty. These probabilistic analyses often require a considerable computational effort and are therefore often not applied in practice to assess existing structures. Hence, in this work, a simplified method will be applied to estimate the remaining load-bearing capacity of an existing structural element and the corresponding uncertainty on this estimate. This method will be based on evaluating uncertainties by application of the ECOV method (Estimation of Coefficient of Variation), which requires only a limited number of model evaluations. This method also allows for determining beforehand, based on the available information, which variables will most influence the uncertainty on the load-bearing capacity of a reinforced concrete element under investigation. This will be illustrated by application to simply supported reinforced concrete beams.

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EXAMPLE APPLICATIONS

The method is illustrated by application to two simply supported reinforced concrete beams subjected to a uniformly distributed load. The first beam has a length of 7800 mm, a width of 350 mm, and a height of 660 mm. The longitudinal bottom reinforcement consists of 4 bars of 25 mm diameter, and the stirrups have a diameter of 8 mm with a spacing of 320 mm. The second beam has a height of 1000 mm, a width of 500 mm, and a length of 6000 mm. The longitudinal bottom reinforcement consists of 6 bars of diameter 25 mm, i.e., one layer of 4 bars and one layer of 2 bars. The concrete cover is 40 mm, and the diameter of the stirrups equals 12 mm, spaced every 500 mm. For both beams, the concrete quality is C30/37, and the reinforcement steel strength is BE500S. The maximum allowable load on the beams is determined based on the limit states related to bending and shear. For the first beam, the bending and shear limit states are close to each other, whereas for the second beam, shear is clearly the governing limit state.

The resisting (M_R) and acting (M_E) bending moments are evaluated according to equation (1).

$$M_R = \theta_{R,M} A_s f_y (h - d_1)\left(1 - \frac{0{,}514 A_s f_y}{b(h - d_1) f_c}\right); M_E = \frac{(q + 25bh)L^2}{8} \tag{1}$$

The resisting (V_R) and acting (V_E) shear forces are evaluated according to equations (2) and (3) [2].

$$\rho = \frac{A_s}{b(h - d_1)}; k = \min\left(2; 1 + \sqrt{\frac{200}{(h - d_1)}}\right) \tag{2}$$

$$V_R = \theta_{R,V} \max\left(b(h - d_1)\left(0{,}18k\left(100\rho_{fc}\right)^{\frac{1}{3}}\right); 0{,}035k^{1,5} f_c^{0,5} b(h - d_1); 2\frac{A_w}{1000} 0{,}9(h - d_1) f_y\right); V_E = \frac{(q + 25bh)L}{2} \tag{3}$$

The limit state equations corresponding to bending and shear failure are respectively given by equations (4) and (5).

$$g_M(X) = M_R - M_E = 0 \tag{4}$$

$$g_V(X) = V_R - V_E = 0 \tag{5}$$

Based on these limit state equations, the resistance of the beam under investigation can be derived as the maximum allowable load q. The mean value and standard deviation of this resistance are determined based on the ECOV method. The mean value is determined based on the mean value of all relevant basic variables, inserted in equations (1) to (*5*). The prior distributions of the considered variables are given in Table 1. All distributions are assumed to be lognormal to avoid negative and hence unrealistic values. The beam dimensions (b, h, and L) are assumed to be deterministic.

Table 1. Prior distributions of variables influencing the maximum allowable load

Var.	Symbol	Distr.	Mean	Stdev.	Ref.
Steel section longitudinal reinforcement	A_s	LN	$A_{s,provided}$	$0{,}02A_{s,provided}$	[3]
Steel section shear reinforcement	A_w	LN	$A_{w,provided}$	$0{,}02A_{w,provided}$	[3]
Centre of gravity of reinforcement with respect to bottom of beam	d_1	LN	$d_{1,provided}$	$0{,}02d_{1,provided}$	[4]
Concrete compressive strength for C30/37	f_c	LN	36 MPa	3 MPa	[4]
Steel yield strength	f_y	LN	560	30 MPa	[4]
Model uncertainty bending	$\theta_{R,M}$	LN	1,2	0,18	[3]
Model uncertainty shear	$\theta_{R,V}$	LN	1,2	0,18	[3]

The coefficient of variation of the resistance, V_q, can be calculated according to equation (6) based on the ECOV method [5], [6].

$$V_q^2 = \sum_{i=1}^{n} \frac{\frac{(q_m - q_{\Delta i})^2}{(\Delta i)^2}\sigma_i^2}{q_m^2} = \sum_{i=1}^{n} V_{q,i}^2 \tag{6}$$

In this equation, i refers to the different variables influencing the maximum allowable load (i.e., the variables in Table 1), q_m is the maximum allowable load when for all variables the mean value is applied, $q_{\Delta i}$ is the maximum allowable load when changing the variable i with an increment Δi, and σ_i^2 is the prior variance of the variable i. The finite variations Δi are evaluated as $\Delta i = \mu_i(1 - \exp(-2{,}15V_i))$, according to [5]. Here, μ_i is the mean of the variable i and V_i is its coefficient of variation (COV).

When applying the ECOV method, the mean value of the resistance equals 53,4 kN/m for beam 1 and 156,4 kN/m for beam 2. The values $V_{q,i}^2$ for the different variables are given in Table 2 for beam 1. When looking at the geometric and material properties, the contribution of the uncertainty on the steel yield strength to the total uncertainty is the largest. Hence, when one wants to achieve a more accurate estimate of the remaining load-bearing capacity, measurements of this property will provide the largest reduction in uncertainty, under the current assumptions. Under different assumptions, these conclusions may vary. An increased prior uncertainty for the concrete compressive strength may vary its importance in the standard deviation of the load-bearing capacity. For example, if the standard deviation of the concrete compressive strength is increased to 12 MPa (and other assumptions are retained), its importance increases from 2.7% to 27.2%, whereas the contribution of the steel yield strength reduces from 8.3% to 6.2%.

It should be pointed out that the ECOV method could be applied considering both the bending and shear limit states together (as is done for achieving the results of Table 2). Nevertheless, when, due to a change in the assumed probabilistic distributions, there could be a shift in the failure mode depending on the size of the finite variations Δi, the ECOV method should be applied considering both limit states separately, i.e. applying it once to the bending limit state and once to the shear limit state.

Table 2. Contribution of the different variables to the total uncertainty on the maximum allowable load based on ECOV for beam 1

Variable	$V_{q,i}^2$ [-]	Percentage of total uncertainty [%]	σ_q [kNm/m]
A_s	5,24e-5	0,17	0,39
A_w	0,00018	0,59	0,73
d_l	1,15e-6	0,0037	0,06
f_c	0,00085	2,73	1,56
f_y	0,0026	8,30	2,72
$\theta_{R,M}$	0	0	0
$\theta_{R,V}$	0,028	88,2	8,88

Based on the ECOV method, the standard deviation of the allowable load q equals 9,46 kN/m for beam 1 and 30,7 kN/m for beam 2. When combining the mean value μ_q and the standard deviation of the remaining capacity of the structure, the design value can be derived. This design value is assessed as $q_d = \mu_q\, exp(-\alpha_q \beta V_q)$, assuming a lognormal distribution. In this equation, α_q is the sensitivity factor, taken equal to 0,8 as a resistance is considered. The reliability index β equals 3,8 for a consequence class 2 and a reference period of 50 years. When applying this equation, the design value of the load under the current assumptions equals 31,2 kN/m for beam 1 and 86,1 kN/m for beam 2.

The results of the ECOV method are also compared with those of a Monte Carlo (MC) sampling method. Here, the distribution of the allowable load is determined with MC sampling (100 000 samples) of the distributions provided in Table 1 and inserting them in equations (1) to (*5*). From the resulting distribution of the allowable load q, the mean value, standard deviation, and design value are determined. These results are summarized in Table 3 for beam 1. Here, it can be seen that the ECOV method gives a good approximation in relation to the Monte Carlo simulation results.

Table 3. Comparison of ECOV and Monte Carlo Sampling for beam 1

	ECOV	Monte Carlo Sampling
μ_q [kN/m]	53,43	54,44
σ_q [kN/m]	9,49	9,16
q_d [kN/m]	31,14	32,65

INFLUENCE OF AVAILABLE DATA

Based on the ECOV method, the influence of additional information on the considered variables can also be derived. In the abovementioned analyses, the distributions are based on literature and hence represent the scatter generally present in the design. Nevertheless, for the assessment of existing structures, more or less prior information can be available, depending on the situation. To investigate the influence of the availability of information, different scenarios are considered:

1) Reinforcement plans are available, and the strength class of the concrete and steel is provided on the design drawings.
2) No reinforcement plans are available; the strength class of the concrete and steel is provided on the design drawings.
3) Reinforcement plans are available; the strength class of the concrete and steel is not provided on the design drawings.
4) No reinforcement plans are available, and the strength class of the concrete and steel is not provided on the design drawings.

These scenarios more or less align with the scenarios mentioned in [7], varying from no record of the original construction to a complete archive of documentation.

Scenario 1

In the first scenario, two situations are considered, assuming different distributions for the reinforcement sections A_s and A_w and the corresponding effective depth d. In the first situation, there is high confidence that the reinforcement plans are correct. Therefore, the COV of the distribution of the reinforcement section is assumed equal to 0,01. In the second situation, the reinforcement plans do not correspond with the actual structure. This could originate from different causes such as the reinforcement plans available do not correspond to the as built situation, or errors have occurred during construction, inducing incorrect reinforcement locations or wrong reinforcement diameters. Hence, in this situation, a larger COV is assumed and taken equal to 0,20 (based on engineering judgement, if more detailed information is available, this value could be determined more accurately). The mean value is also reduced, since it is less likely that more reinforcement will be present than indicated on the design plans. The mean value is reduced to the average of the minimum expected reinforcement and the amount indicated on the design plans. For both situations, a distribution for the maximum allowable load can be retrieved. These will be weighed with the probability of occurrence of each of the situations. In this work, it will be assumed that there is a 75% probability that the reinforcement plans are correct, and a 25% probability that the reinforcement plans were not followed during construction.

For beam 1, it was found that the ECOV method should be applied to the bending and shear limit states separately. For the first situation, i.e., where the reinforcement plans are assumed to be correct, the mean of the estimated load is 53,4 kN/m, the standard deviation equals 9,4 kN/m, and the design value is equal to 31,3 kN/m. For the second situation, i.e., where the reinforcement plans are assumed not to be correct, the values are 53,5 kN/m, 16 kN/m, and 21,6 kN/m, respectively. The resulting weighted design value is evaluated as 28,9 kN/m. For beam 2, for situation 1 (i.e., reinforcement plans are assumed to be correct), the mean value of the allowable load is 156,4 kN/m and the standard deviation equals 30,5 kN/m, leading to a design value of 86,5 kN/m. In the second situation (i.e., reinforcement plans are assumed not to be correct), the mean value of the load equals 134,0 kN/m, the estimate of the uncertainty on the allowable load increases to 40,3 kN/m, and the design value decreases to 53,7 kN/m. When the resulting weighted design value is evaluated, this equals 78,3 kN/m.

Scenario 2

In this scenario, it is assumed that there are no reinforcement plans available. Hence, assumptions should be made on the reinforcement that is present in the section. One assumption is to perform the analysis assuming the minimum value of the reinforcement that should at least be present based on the design guidelines at the moment of construction of the considered building. Another option is to try to determine the loads that were taken into account during design (e.g., based on calculation reports, notations on the construction plans, or based on the intended use of the building and the original permanent loads which could be derived from the architectural plans). Based on these loads and the design guidelines from the time of construction, the required amount of reinforcement could be derived. It should be pointed out that both strategies will likely always result in lower-bound conservative estimates of the resistance, leading to a 'downscaled design'. For the beams under investigation, assuming design according to the current generation of Eurocodes [2], the required reinforcement ranges from 339 mm² to 1963 mm² for beam 1, and from 700 mm² to 2945 mm² for beam 2. Hence, a distribution with a mean value of the average of the upper and lower bound will be assumed, and a standard deviation will be determined such that the difference between the minimum reinforcement and the mean value of the distribution equals 3 times the standard deviation. The distributions for the lever arm and for the shear reinforcement are adjusted correspondingly.

For beam 1, this results in a design value of the maximum allowable load of 21,5 kN/m (mean value 53,5 kN/m and standard deviation 16,1 kN/m). For beam 2, this scenario results in a design value of the maximum allowable load of 70,6 kN/m (mean value 134,0 kN/m and standard deviation 28,2 kN/m). Hence, besides deriving a reduced design value compared to scenario 1, the ECOV method provides an indication of the expected mean and standard deviation of the maximum allowable load, more accurately accounting for uncertainties in the available information.

Scenario 3

In the third scenario, again, two situations are considered with respect to the reinforcement layout, similar to scenario 1. However, in contrast to scenario 1, now the material properties are not known. Regarding the concrete strength, it is assumed that the actual applied concrete class will range from C20/25 to C30/37. Hence, the mean value is assumed to correspond to the mean value of strength class C25/30, i.e., 33 MPa, but a large uncertainty is assumed with a standard deviation of 12 MPa. Similar for the yield strength, the mean value is reduced to an average for BE400S and BE500S. For beam 1, this leads to a weighted design value of the maximum allowable load of 12,1 kN/m (situation 1: mean 49,9 kN/m, standard deviation 22,1 kN/m, and design value 13 kN/m; situation 2: mean value 48,2 kN/m, standard deviation 25,8 kN/m, and design value 9,5 kN/m). For beam 2, for the first situation, the design value equals 33,7 kN/m, resulting from a mean value of 141,4 kN/m and a standard deviation of 66,7 kN/m. For the second situation, the design value equals 24,2 kN/m, resulting from a mean value of 120,9 kN/m and a standard deviation of 64,0 kN/m. The weighted design value equals 31,3 kN/m.

Scenario 4

In the last scenario, there is no information on the strength properties or the reinforcement layout. The distributions for the reinforcement are the same as those assumed for scenario 2. For the material properties, the distributions from scenario 3 are considered. This results in a design value of the maximum allowable load of 9,5 kN/m for beam 1 (mean value 48,2 kN/m, standard deviation 25,7 kN/m). For beam 2, this results in a design value of the maximum allowable load of 28,0 kN/m, with a mean value of 120,9 kN/m and a standard deviation of 58,2 kN/m.

Discussion

In Table 4, the resulting design loads for the different scenarios and the two beams are summarized. Here, it can be seen that the maximum allowable load is smallest when there are no reinforcement plans available and there is no information on the material properties (scenario 4). When there is information on the reinforcement, the estimated design value of the allowable load increases by 27% for beam 1 and by 13% for beam 2. When only information on the material properties is available, the design value increases by 127% for beam 1 and by 154% for beam 2. When both types of information are available, the maximum allowable load is highest, i.e., an increase of 204% compared to the situation with no information for beam 1 and with 182% for beam 2. Scenario 1 gives an increase of 139% compared to the situation where there is only reinforcement information for beam 1 and an increase of 150% for beam 2. Finally, scenario 1 leads to an increase of 34% compared to the situation where there is only information on the material properties for beam 1 and an increase of 11% for beam 2. Hence, for the specific investigated situations and the assumed uncertainties, the information from the material properties is more valuable than the information with respect to the reinforcement layout.

Table 4. Summary of the different scenarios

	Beam 1				Beam 2			
Scenario	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
q_d [kN/m]	28,9	21,5	12,1	9,5	78,3	70,6	31,3	27,8
Reinforcement plans	Yes	No	Yes	No	Yes	No	Yes	No
Material information	Yes	Yes	No	No	Yes	Yes	No	No

CONCLUSION

In this paper, a simplified method is proposed to determine the distribution of the load-carrying capacity of a reinforced concrete beam, together with the resulting design value. The method is based on the ECOV method, providing an estimate of the variance. The advantage of this method is illustrated by its application to four different scenarios, considering a varying amount of available information. From the analyses, it could be concluded that a main advantage of the ECOV method is that it not only provides an estimate of the design value of the load carrying capacity, but also of the mean value and the uncertainty on the prediction. Moreover, from the examples considered in this work, under the assumptions made here, it was found that, in general, information from material properties is more valuable compared to information on the reinforcement layout. This might be beneficial, since these are easier to test in an existing structure. It should be pointed out that all analyses in this work assume that no non-destructive test methods for estimating material properties and reinforcement configurations are accounted for. However, the prior estimation of the most influential parameters when evaluating the uncertainty in the estimated load-carrying capacity allows us to determine which parameters the uncertainty will preferably be reduced. As such, decisions can be made to implement additional (non-destructive) testing where necessary.

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