Probabilistic Modelling of HSC Slender Columns in High-Rise Buildings

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Summary

In Europe high performance concrete has been used successfully since 1990. The extremely high compressive strength of this material allows considerable reduction of cross-sectional dimensions of reinforced concrete columns and accordingly fulfils highest architectural and functional requirements. This leads to extremely slender members and therefore increases the risk of failure due to loss of stability in many cases. Because of the positive experience with high performance concrete up to now, the current study questions current conservative design provisions. In this context code procedures of Eurocode 1 as well as Eurocode 2 are compared with the results of probabilistic analysis and potentials for optimization will be indicated.

Keywords: probabilistic design, load model, slender columns, high performance concrete, safety, reliability

1. Modelling of Live Loads in High Rise Buildings

Due to the strong scatter of live loads, the influence of the live loads on the structural reliability is large compared to the influence of the dead loads which can be easily predicted over the service life of the structure. The design regulations according to EN 1992-1-1 (Eurocode 1) provide easy to use design loads for use in practice which account for the dependencies of the stochastic load parameters in an approximate way. Because of the required idealizations and simplifications it cannot make use of all advantages of stochastic modelling of the live loads.

In most standards and guidelines, it is required that the characteristic value of the extreme value distribution of the live loads does not exceed the 98%-tile in an observation period of 1 year. With increasing influence area, the standard deviation of the live load decreases and so the corresponding quantile of the live load decreases as well. This leads to the possibility of reduction of the live load in case of large influence areas by use of the factor α_A according to EN 1991-1-1, 6.3.1 (6.1). In the case of high rise buildings, it is assumed that the intensity of the live load is not the same on different floors, so that addition of the extreme value distributions of the live loads is not appropriate. If the live loads on different floors govern the design of a vertical member, EN 1991-1-1, 6.3.1 (6.2) allows a reduction by the factor α_N. According to the design regulations, simultaneous use of α_A and α_N is not established yet.

Based on numerical investigations, it was found that in both cases (α_A and α_N) the probabilistic model results in larger reductions than the European Standard. Furthermore, it can be recognized from the results of the probabilistic analysis that the reduction per floor is influenced by the respective influence area. At this point, a significant potential for optimization accounting for combined application of the reduction factors is found. This would result in more economic structures in the case of high rise buildings.

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2. Modelling of slender HSC columns resistance

For realistic modelling of the load bearing behaviour of slender RC columns, material and geometric nonlinearities have to be considered. Material nonlinearity means the stiffness reduction with increasing load intensity and geometric nonlinearities result from second order effects. Due to the load dependant material behaviour (moment-curvature-relationship) a sudden stability failure may occur long before material strength is exceeded. In these cases we speak of stability failure due to load dependant stiffness reduction. For correct analysis of the described phenomena the use of realistic material laws are inevitable. Concerning the probabilistic model of high strength concrete, it has to be mentioned that in the past, statistical information on the variability of the compressive strength was rarely available. A recent study by Tue et. al. delivers new interesting findings about the standard deviation of the concrete compressive strength. One important result is that the standard deviation compared to earlier studies has decreased by about 1.2 MPa which is owed to the increasing use of ready-mixed concrete. Furthermore, the standard deviation of high strength concrete is marginally higher than that of normal strength concrete. A regression analysis delivered a non-linear correlation equation between the coefficient of variation of the concrete compressive strength and the nominal value of the concrete strength.

The reliability analysis presented in the current study concentrates on short (slenderness ratio $\lambda = 0$) and slender (slenderness ratio $\lambda = 100$) high strength concrete columns, with a nominal compression strength of $f_{ck} = 100$ MPa. The cross-sectional dimensions are $b/h/d_1 = 40/40/4$ cm and the total reinforcement ratio is defined as $\rho_{tot} = 1\%$. Further parameters are the ratio between the characteristic live load and dead load Q_k/G_k as well as the eccentricity ratio e/h of the applied axial load. The analysis is carried out with the help of the Adaptive Importance Sampling Method.

Fig. 1 shows the calculated safety index β for HSC columns with a nominal concrete compression strength of $f_{ck} = 100$ MPa. The short columns ($\lambda = 0$) reveal a sufficient reliability level of $\beta = 4.7$ for the eccentricity ratio $e/h = 0.1$. With increasing eccentricity the reliability index declines to 4.2 at an eccentricity ratio of $e/h = 2.0$. This value lies in the accepted range of variation according to Eurocode 1. The slender column type ($\lambda = 100$) on the other hand shows a significant reduction of the reliability index $\beta = 3.5$ at $e/h = 0.4$ and Q_k/G_k=0.25. The corresponding sensitivity factors reveal that only stiffness determining variables are of major influence, what is a clear sign of stability failure. This serious reliability gap is not acceptable, since stability failure occurs without any prior notice by e.g. increasing deflection and crack formation. The different partial safety factors for steel and concrete become ineffective in the case of stability failure where neither the steel yield strength nor the concrete compressive strength is reached. Therefore the authors recommend the use of a safety format which works with only one safety factor γR on the resistance side of the design equation, according to Eurocode 2, Part 2 (bridges) or ACI 318.

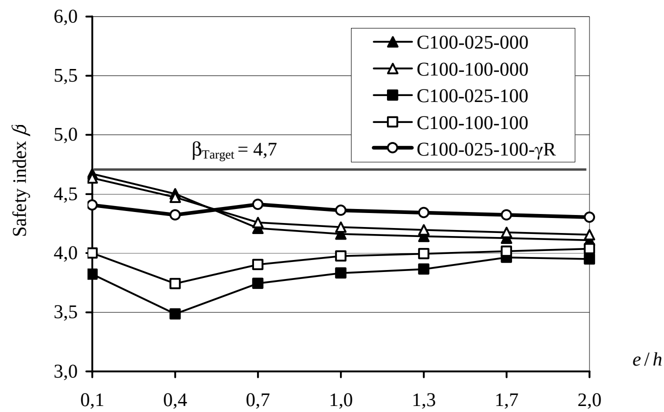

Fig 1: Safety Index β for HSC columns (caption: Concrete strength - Q_k/G_k - λ)