Impact of concrete compressive strength on the reliability and the plastic moment of steel-concrete composite beams

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Abstract:

Introduction/purpose: This study investigated the influence of concrete compressive strength on the reliability and the plastic resistance moment of steel-concrete composite beams. The objective was to evaluate the impact of concrete strength variations on structural performance, with a particular attention to the plastic resistance moment which is critical to the safety and compliance of the composite beam.

Methods: To model the nonlinear behavior of concrete, Abaqus created a three-dimensional numerical model including a concrete damage plasticity (CDP) model. Reliability analysis was performed, and the failure probability was assessed using Monte Carlo simulations (MCS) and first-order (FORM) and second-order (SORM) reliability methods. The limit state function was determined according to Eurocode 4 criteria considering the concrete compressive strength of 25 to 80 MPA.

Results: As a result, it was found that the compressive strength of concrete significantly affects the plastic resistance moment and the reliability index of the composite beam. The high strength of concrete improves the plastic resistance moment, and the reliability index varies depending on the geometric and material property of the composite section and loading conditions.

Conclusion: The compressive strength of concrete is an important parameter that determines the structural characteristics and safety of steel-concrete composite beams. This highlighted the need to consider the variability of concrete strength when designing and evaluating composite structures to ensure compliance with reliability standards.

Key words: composite beam, nonlinear modelling, plastic resistance moment, reliability analysis, finite element analysis, failure probability.

Introduction

Due to the combination of concrete compressive strength and steel tensile strength, steel-concrete composite beams are frequently utilized in moderne construction to create reliable and efficient systems. The behavior of these beams is strongly influenced by concrete compressive strength which also affects their plastic resistance moment and reliability. The purpose of this study is to examine how these two crucial factors are affected by the compressive strength of concrete.

Many researchers use a limit state function based on Eurocode 4 criteria (CEN, 1994) to study the reliability of steel-concrete composite beams. The goal of this strategy is to offer more precise insights into the behavior of the system under study. Using a case study as validation, Mamuda et al. (2018) examined the four failure modes of bending, shearing, deflection, and shear connector capacity when analyzing the reliability of beams. The impact of various parameter variations on reliability was evaluated. Chaves et al. (2010) examined the design specifications for the steel-concrete composite beam. The study of the structural reliability of the timber concrete composite beam is evaluated by Daanoune et al. (2024). This evaluation is carried out by the MCS, the FORM and the SORM methods for three failure modes in concrete, timber and at the connectors. Another research where the limit state function is based on the resistance criteria according to Eurocode 4 was carried out by Lydia & Nassim (2022). This study focuses on the evaluation of the reliability of square composite columns under axial compression and the results show that steel tubular columns filled with high performance concrete (HPCFTC) are more reliable than those filled with ordinary concrete (OCFSTC).

In this context, the study provides a comprehensive analysis using numerical simulations to investigate the influence of concrete tensile strength. A 3D finite element model has been developed in Abaqus to simulate the behavior of composite beams to account for the nonlinear behavior of concrete in tension and compression through Concrete Damage Plasticity - CDP (Dassault Systèmes, 2016; CEN, 2004). The reliability analysis is performed using the Monte Carlo simulation (MCS) and the first-order (FORM) and the second-order (SORM) reliability methods, as developed by Rackwitz (2001), which include the treatment of uncertainties in the parameters affecting the system behavior. The applied limit state functions are designed to verify the plastic resistance moment of the composite beam in bending, in accordance with Eurocode 4 standards (CEN, 1994). The study considers a range of concrete compressive strengths from 25 to 80 MPa. The results demonstrate a significant influence of concrete compressive strength on reliability and plastic moment capacity. This study provides valuable insights into the design and analysis of steel-concrete composite beams, enabling the optimization of their performance and safety, and proposes a clear approach to the use of safety factors to adjust the reliability level of the system, thereby ensuring the proper functioning of the composite beam.

Methodology

Plastic resistance moment of the composite cross section to bending

The calculation of the neutral axis depth Z_{pl} and the determination of the plastic neutral axis (PNA) position according to Eurocode 4 (CEN, 1994; Johnson, 2018; Liang, 2018) allows for the calculation of the plastic resistance moment $M_{pl,Rd}$ of the composite section. This procedure is performed using the following equations.

If the neutral axis is located in the concrete slab

$$Z_{pl} = \frac{N_{pla}}{b_{eff} \times 0.85 \times f_{cd}} \quad (1)$$

$$M_{pl,Rd} = N_{pla}\left(\frac{h_a}{2} + h_c - \frac{Z_{pl}}{2}\right) \quad (2)$$

where:

$$N_{pla} = A_a \times \frac{f_y}{\gamma_a} \quad (3)$$

$$f_{cd} = \frac{f_c}{\gamma_c} \quad (4)$$

b_{eff}: effective width of the concrete flange,
γ_a: safety factors of steel,
γ_c: safety factors of concrete,
f_y: yield strength of the steel section,
f_c: compressive strength of the concrete,
h_a: height of the steel section,
h_c: height of the concrete flange,
A_a: area of the steel section, and
if the neutral axis is located in the steel flange

$$Z_{pl} = \frac{N_{pla} - N_{cf}}{2 b_f \times f_y} \times \gamma_a + hc \quad (5)$$

$$M_{pl,Rd} = N_{pla}\left(\frac{h_a}{2} + \frac{h_c}{2}\right) - \left(N_{pla} - N_{cf}\right)\frac{Z_{pl}}{2} \quad (6)$$

where:

$N_{cf} = \frac{0.85.f_c}{\gamma_c} \times h_c \times b_{eff}$ ....(7)

b_f: width of the steel flange.

Composite cross section design

For the study of the flexural behavior of steel-concrete composite beams, four types of composite steel-concrete beams were tested by Du et al. (2021), each with a different class of concrete: C25, C45, C65, and C80 with a compressive strength of 24.5 MPa; 45.9 MPa; 63.1 MPa and 78.3 MPa, respectively. Figure 1 illustrates the layout and the transverse and longitudinal dimensions of the steel-concrete composite beam with the stud connection. The beam is subjected to four-point bending, with one end pinned and the other end on a roller.

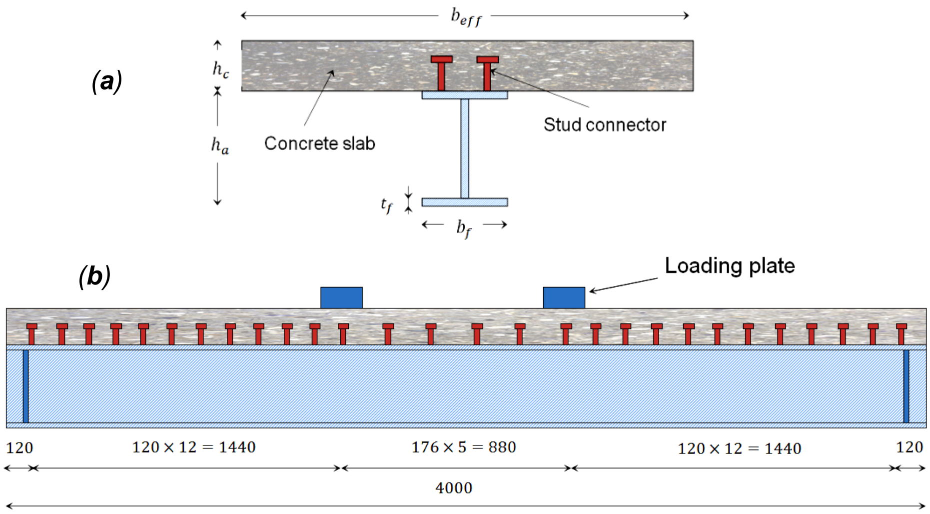

*Figure 1 – Cross-sectional dimensions of composite beams: (**a**) cross-section; (**b**) longitudinal section*

Finite element analysis (FEA) setup and parameters

These samples are modeled using a 3D finite element (FE) model with Abaqus software (Dassault Systèmes, 2016). In the FE models, damage plasticity was used to simulate the mecanical behavior of concrete. Cracking or crushing of concrete results in a reduction of its elastic modulus. The tensile behavior of concrete was assumed to be linear up to the uniaxial tensile strength $f_t = \frac{f_c}{10}$ according to Eurocode 2 (CEN, 2004). The uniaxial stress-strain relationship in compression for concrete can be identified by the following formula of Hognestad Model (Hognestad, 1951):

$\sigma_c = f'_c \times \frac{\varepsilon}{\varepsilon_0} \times \left(2 - \frac{\varepsilon}{\varepsilon_0}\right)$ for $\varepsilon \leq \varepsilon_0$……………………………(8)

$\sigma_c = f'_c \times \left[1 - 0.15\left(\frac{\varepsilon - \varepsilon_0}{\varepsilon_{cu} - \varepsilon_0}\right)\right]$ for $\varepsilon > \varepsilon_0$ ……………………..….(9)

where $\varepsilon_{cu}$is the ultimate compressive strain and $\varepsilon_0 = \frac{2 \times f'c}{E}$ is the strain at the ultimate stress according to Hognestad Model, see (Hognestad, 1951). This model has been used and mentioned in the papers of several authors such as Guo et al. (2020) and Rezaie et al. (2022).

$E_{cm}\,[MPa] = 22000 \times \left(\frac{fcm}{10}MPa\right)^{0.3}$: the elasticity modulus of concrete given by Eurocode 2, Table 3.1 (CEN, 2004).

f'_c: the ultimate concrete compressive stress.

The steel material properties of the steel beam and the screw stud connectors were defined as isotropic elastoplastic behavior (Dassault Systèmes, 2016). The yield strength and ultimate tensile strength of the studs were 350 MPa and 480 MPa and the yield strength and the ultimate tensile strength of the steel beam were 495.4 MPa and 572 MPa (Du et al, 2021).

Probabilistic methods for the reliability analysis

Three different methods were employed: the Monte Carlo method, the FORM, and the SORM.

The Monte Carlo simulation is practical and accurately represents the real phenomenon during a sample test. The principle of this method involves generating a large number of simulations, typically in the order of 10^n(Haldar & Mahadevan, 1999) to calculate the failure probability $P_f$using the equation:

$P_f = \frac{Nf}{N}$ …………………………………..……(10)

where Nf is the number of times the system fails, and N is the total number of simulations. In our study, à MATLAB command was used to generate à number N of simulations with a given mean and standard deviation.

The FORM Method: This method is a first-order Taylor series expansion of the limit state function $G(x)$ around a point P^*, called the design point. It involves determining the reliability index β, which is the shortest distance between the origin O and the point P^* in the centered standard space. The reliability index β then provides access to an approximate failure probability P_f (Grandhi & Wang, 1999). The reliability index was calculated using the Hasofer-Lind-Rackwitz-Fiessler algorithm:

$$\beta = \min_{g(u)=0} \sqrt{\sum_{i=1}^{n} u_i^2} \quad (11)$$

$$P_{f,FORM} = \Phi(-\beta) \quad (12)$$

where Φ is the cumulative distribution function - CDF (Grandhi & Wang, 1999), see Appendix 1.

The SORM Method: This method is a second-order Taylor series expansion of the limit state function $G(x)$ and corrects the failure probability obtained by the FORM. For this method, we used the Breitung formula to calculate P_f (Haldar & Mahadevan, 1999):

$$P_{f,SORM} \approx \Phi(-\beta) \prod_{j=1}^{n-1} \frac{1}{\sqrt{1+\beta k_j}} \quad (13)$$

We define the principal curvatures k_j as the eigenvalues of the matrix A , where its elements a_{ij} are defined by:

$$a_{ij} = \frac{(RDR')_{ij}}{|\nabla G(U^*)|} i, j = 1,2,3, \dots, n-1 \quad (14)$$

Here, D is the Hessian matrix $(n \times n)$ of the limit state function in the reduced centered normal space evaluated at the design point. R is the rotation matrix obtained by the Gram-Schmidt transformation (Haldar& Mahadevan, 1999), see Appendix 6.

Mechano-reliability coupling

The mechano-reliability coupling of Abaqus-MATLAB is used to evaluate the flexural failure mode of composite beams according to Eurocode 4 (CEN, 1994) Abaqus simulates the behavior of the mechanism related to material interaction and nonlinearity, while MATLAB does reliability analysis, focusing on the flexural over the failure mode of the limit state functions. This approach takes into account the uncertainties in the properties of certain geometric and material parameters, determining the probability of reaching the moment of plastic resistance and guaranteeing compliance with the safety criteria.

In our reliability study, we distinguish two limit state functions according to the position of the neutral axis

$$G_1(x) = N_{pla}\left(\frac{h_a}{2} + h_c - \frac{Z_{pl}}{2}\right) - M_{sd} \quad (15)$$

$$G_2(x) = N_{pla}\left(\frac{h_a}{2} + \frac{h_c}{2}\right) - \left(N_{pla} - N_{cf}\right)\frac{Z_{pl}}{2} - M_{sd} \quad (16)$$

Table 1 – Random variables chosen from the limit state function

Properties	Variables	Mean	COV	Distribution	Ref.
Material	f_y	$495.4\ \mathrm{N/mm^2}$	6%	Lognormal	Bartlett et al. (2003)
	f_c	$24.5\ \mathrm{N/mm^2}$	6%	Lognormal	Bartlett et al. (2003)
Geometric	h_a	$250\ \mathrm{mm}$	5%	normal	Ellingwood et al. (1982)
	h_c	$100\ \mathrm{mm}$	5%	normal	Ellingwood et al. (1982)
Loading	M_{sd}	$355.68\ \mathrm{KN.m}$	5%	normal	Du et al. (2021)

The following flowchart explains the Abaqus-MATLAB coupling steps:

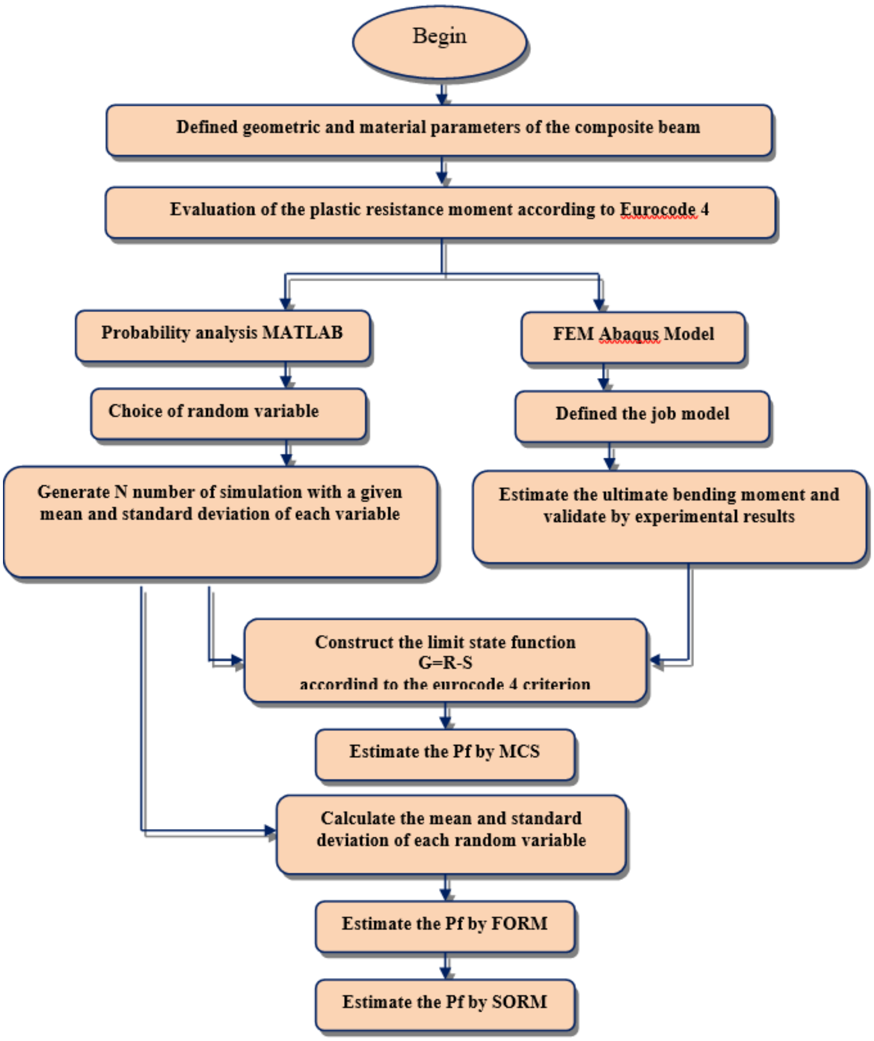

Figure 2 – Abaqus-MATLAB mechanical-reliability coupling flowchart

Results and discussion

Abaqus and the reliability results

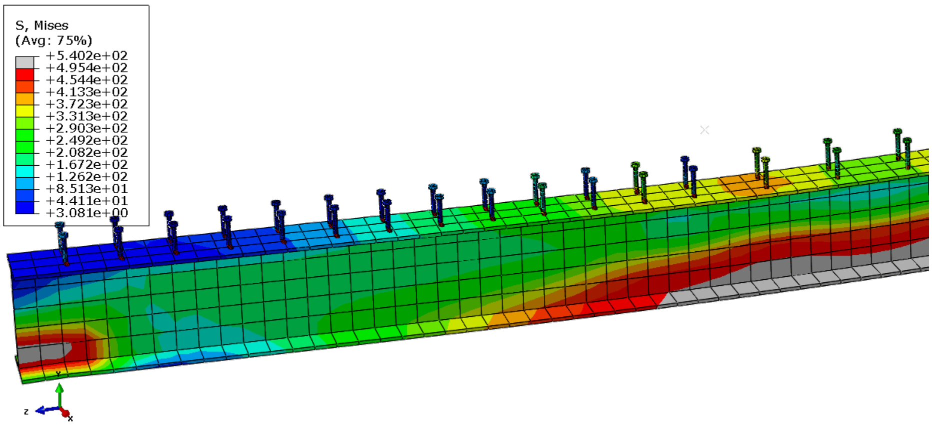

Figure 3 –Stress distributions in the connection at the maximum load

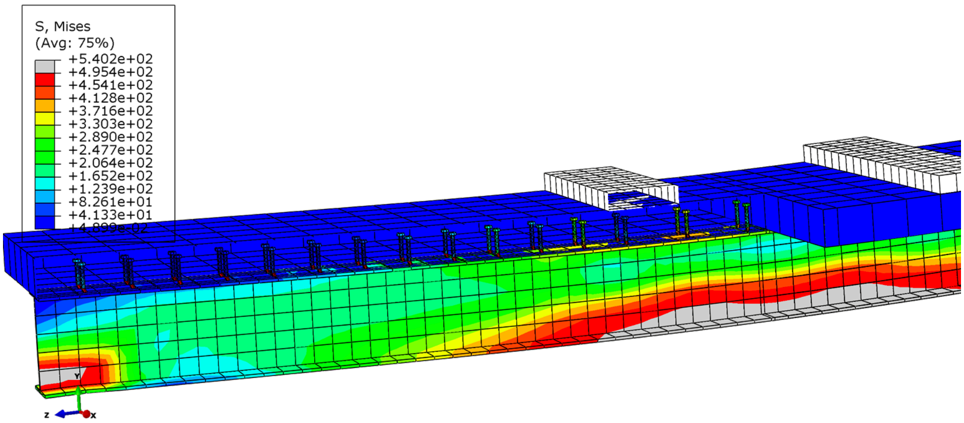

Figure 4 – Stress distributions in the composite beam with a 3D cut view

Figures 3 and 4 illustrate the stress distribution within the composite beam under the maximum load. Across the four types of beams studied, it was observed that the neutral axis is consistently located near or within the thickness of the concrete slab. This suggests that the bottom fiber of the steel beam is yielded before the concrete reaches its maximum compressive strength. This prediction is confirmed by the Abaqus results of the finite element analysis, Figures 3 and 4 (in gray), which show that the bottom fiber in the middle of the steel beam has reached its maximum strength of 495.4 MPa.

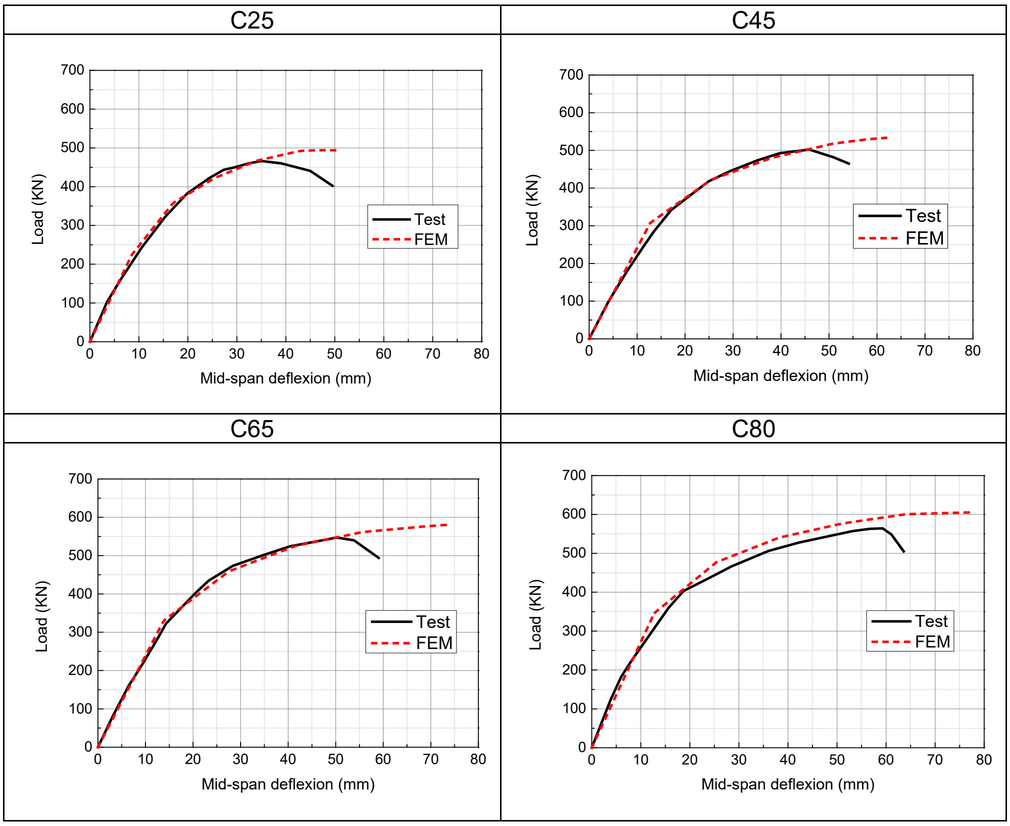

Figure 5 – Load-deflexion curve with different concrete classes of the composite beam

Figure 5 compares the mid-span load-deflection curves of the beam obtained by a nonlinear method and the experimental results given by Du et al. (2021). In all four composite beam samples, the finite element simulation (FEM) accurately estimated the curve of the experimental part and thus provided a globally consistent estimate of the composite beam behavior under load. It offers the possibility to thoroughly analyze the different stages of structural deformation and to visualize the behavior up to the ultimate loading phase, which is difficult to accomplish by experimental tests alone. However, the slight overestimation of ductility observed in the FEM simulation results compared to the experimental data can be explained by the use of simplified elastoplastic laws to represent the behavior of steel. The force-deflection curves of steel-concrete composite beams in nonlinear analysis do not have a descending branch in this study due to the ductility of steel and the application of an elastoplastic or bilinear constitutive law, which influences the curve by delaying the formation of a decreasing branch. Steel can reach its plastic domain without immediately losing its strength. Indeed, once the steel enters its plastic phase, the stiffness of the beam decreases, and the force-deflection curve tends to stabilize or become horizontal. This type of curve is observed by Chiorean & Buru (2017) and Benyahi et al. (2021) and by Luo et al. (2012) which confirms the results obtained in the FEM model studied.

Table 2 – Plastic resistance moments for each concrete class

Specimen	Plastic resistance moment (kN.m)M_{plRd}		Ultimate Abaqus moment (kN.m)	Ultimate experimental moment (kN.m)	$\frac{M_{abaqus}}{M_{exp}}$
	for γ_c=1	for γ_c=1.5			
C25	365.87	332.0336	355.68	341.3	1.04
C45	422.79	388.9604	392.41	378.8	1.03
C65	441.23	416.6237	423.68	408.8	1.04
C80	450.785	430.9544	432.45	423.8	1.02

Table 3 – Reliability indices and probabilities of failure

Specimen	Abaqus		
	MCS	FORM	SORM
C25	$P_f = 0.3509$	$\beta = 0.3443$ $P_f = 0.3653$	$P_f = 0.3571$
C45	$P_f = 0.0043$	$\beta = 2.6184$ $P_f = 0.0044$	$P_f = 0.0043$
C65	$P_f = 1.1700e-04$	$\beta = 3.7918$ $P_f = 7.4775e-05$	$P_f = 7.2567e-05$
C80	$P_f = 4.0000e-06$	$\beta = 4.4518$ $P_f = 4.2580e-06$	$P_f = 4.1438e-06$

Table 2 presents a comparison between the ultimate moment obtained by theory and the test. The results demonstrate a good agreement between the experimental ultimate moments and those calculated with Abaqus, which confirms the used simulation method. The observed ratios M_{abaqus}/M_{exp} are relatively low and fluctuate between 1.02 and 1.04, which is generally acceptable compared to 1.01 found by Du et al. (2021) and Mans et al. (2001), as well as between 0.95 and 1.05 for Nie et al. (2009) and 1.03 for Youn et al. (2011). According to the results of Table 3, it is evident that the reliability of steel-concrete composite structures varies considerably depending on the quality of the concrete used. For concrete class C25, the probability of failure is high $P_f = 0.3509$, indicating low structural reliability. Increasing the concrete class C45, C65, C80 results in a decrease in the probability of failure $P_f = 0.0043$, $1.1700e-04$, $4.0000e-06$, while the reliability index β increases $\beta = 0.3443, 2.6184$, 3.7918 , 4.4518, indicating increased strength and safety. Consistent results are obtained using different techniques, the MCS, the FORM and the SORM, confirming that composite beams with high-quality concrete slabs C65 and C80 are more reliable than those with low-quality concrete slabs C25. In summary, the choice of high-quality concrete, such as C65 and C80, ensures strong structural performance and increased reliability, making these composite beams ideal for supporting high loads and meeting strict safety requirements. The reliability results obtained by the FORM, the SORM and the MCS also show that when the limit state functions are nonlinear, the SORM method provides a better approximation than the FORM. Indeed, the SORM considers the limit state surface as a curve shape (hyperboloid), while the FORM simplifies it into a tangent plane. This more realistic approach allows the SORM to obtain results very close to those of the Monte Carlo method known for its high accuracy. The studies of Yu et al. (2017) and Morse et al. (2017) corroborate these results.

According to Eurocode 2 and many international codes and regulations (fib, 2013; The Government of the Hong Kong Special Administrative Region: Buildings Department, 2020; ACI Committee 318, 2019) the safety factor $\gamma c = 1.5$ is used in structural calculations to ensure a certain level of reliability by reducing the characteristic strength of concrete. This explains the inherent uncertainties due to the design and measurement during construction. In this study, we used the actual mean values of the geometric and material parameters for the reliability analysis, while taking into account the uncertainties by integrating the standard deviation of these parameters. The results of the reliability analysis (Figure

7) and the plastic resistance moments (Figure 6) for $\gamma c = 1$ and $\gamma c = 1.5$ were compared to evaluate the safety margins provided in the calculations according to Eurocode 4.

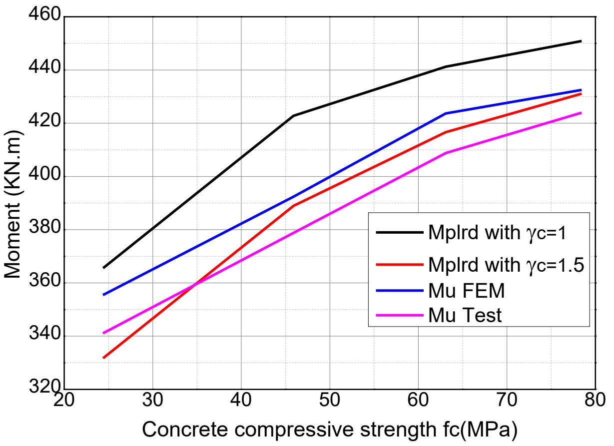

Figure 6 – Moment variation as a function of the concrete compressive strength

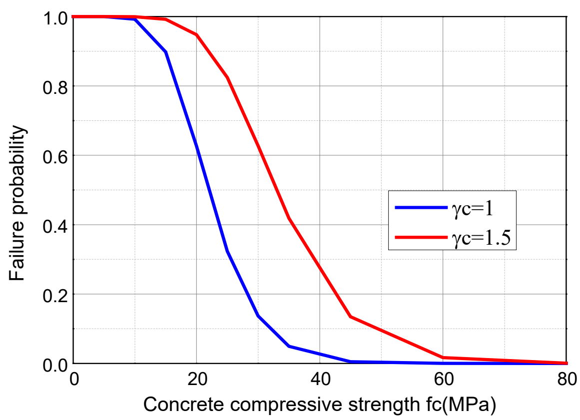

Figure 7 – Variation in failure probability as a function of the concrete compressive strength

As shown in the curve in Figure 7, the safety factor has a significant impact on the reliability index, which is based on the concrete compressive strength. When $\gamma c = 1$, the initial reliability index is high, but it decreases

as the concrete strength decreases, indicating a decrease in structural safety margins and an increased probability of failure when the concrete compressive strength is low. This decrease is particularly noticeable when f_c values are around 20 MPa.
In contrast, when $\gamma c = 1.5$, the reliability index remains higher overall f_c, indicating a more robust design with higher safety margins. Even at higher concrete strengths, where the index $\gamma c = 1$ becomes critical, $\gamma c = 1.5$ ensures significantly higher reliability. According to Eurocode standards, the results demonstrate the importance of using an appropriate safety factor to ensure good structural reliability.

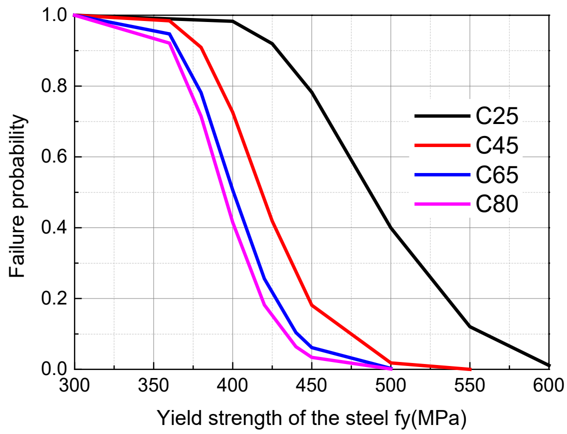

Figure 8 – Variation in failure probability as a function of the yield strength of steel

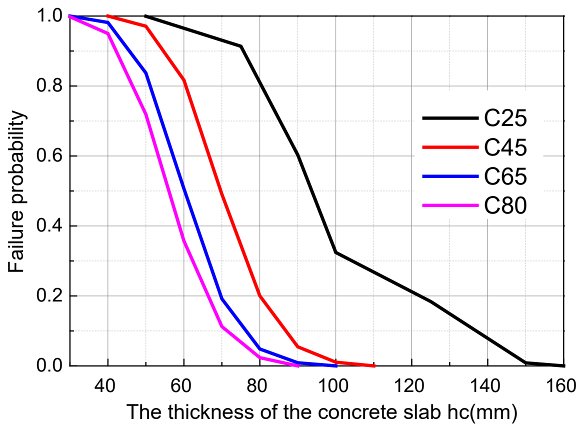

Figure 9 – Variation in failure probability as a function of the concrete slab thickness

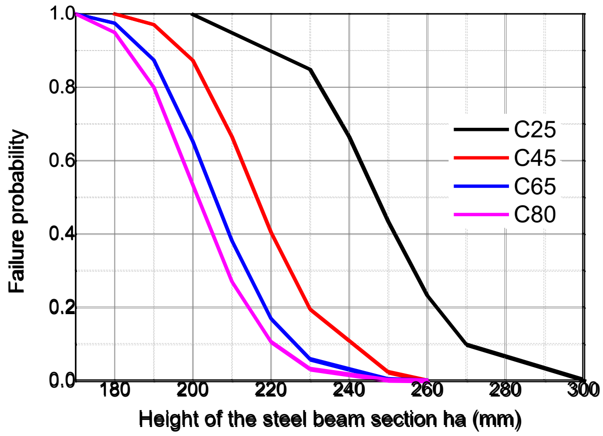

Figure 10 – Variation in failure probability as a function of the steel beam height

The results of the three last Figures (8, 9 and 10) show that several factors influence the probability of failure P_f of the steel concrete composite beam. First, an increase in the steel beam strength generally leads to a decrease in failure probability (Figure 8) because stronger steel increases the structural performance. This decrease is even more pronounced when the concrete has a high strength C45, C65 or C80, because stronger concrete requires stronger adhesives to maximize its potential. In parallel, a higher section height of the composite section, whether concrete (Figure 9) or steel (Figure 10) reduces failure probability while improving the stiffness of the beam. The probability of failure decreases with increasing height for all types of concrete, with a stronger effect for high-strength concrete, which exhibits superior performance even at lower section heights. Therefore, increasing the overall height of the composite section and improving the strength of the steel beam significantly reduces the probability of failure of the composite system, with benefits that are particularly evident when the concrete is high strength.

Conclusion

The evaluation of steel-concrete composite beams reveals several essential insights into their structural reliability and performance. The finite element method (FEM) has demonstrated high accuracy in predicting the behavior of composite beams under load, by closely aligning with experimental results. The FEM remains a valuable tool to analyze structural deformation steps and predict failure outcomes.

The comparison between the original values and the experiments confirms the simulations using the FEM and maintains a good conformational system. Notably, the failure probability P_f is a sign that the high-strength concrete is used. The concrete classes C45, C65 and C80 have a safer and more reliable system than the concrete C25. This trend relieves the import of high-strength concrete to increase the structure performance and safety.

Furthermore, the results highlight that increasing the section height of both concrete and steel components reduces the failure probability P_f, thereby improving beam stiffness and overall reliability. The benefits of these design adjustments are more pronounced with high-strength concrete, which retains its performance advantages even at smaller section heights.

The results highlight the importance of selecting high-strength materials and optimizing section dimensions to improve the safety and reliability of composite beams, aligning with Eurocode standards and ensuring robust structural performance.

References

-ACI Committee 318. 2019. *ACI CODE-318-19(22): Building Code Requirements for Structural Concrete and Commentary (Reapproved 2022)* [online]. Availble at: https://www.concrete.org/store/productdetail.aspx?ItemID=318U19 [Accessed: 14 November 2024]

Bartlett, F.M., Dexter, R.J., Graeser, M.D., Jelinek, J.J., Schmidt, B.J. & Galambos, T.V. 2003. Updating Standard Shape Material Properties Database for Design and Reliability. *Engineering Journal*, 40(1), pp.2-14. Available at: https://doi.org/10.62913/engj.v40i1.800.

Benyahi, K., Bouafia, Y., Oudjene, M., Barboura, S. & Kachi, M.S. 2021. Numerical Procedure for the Three-Dimensional Nonlinear Modelling of Composite Steel–Concrete Beams. *International Journal of Steel Structures*, 21(3), pp.1063-1081. Available at: https://doi.org/10.1007/s13296-021-00490-1.

-CEN (The European Committee for Standardization). 1994. *CEN ENV 1994-1-2:1994(MAIN) Eurocode 4: Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design* [online]. Available at: https://standards.iteh.ai/catalog/standards/cen/6476197f-10f8-435d-8813-683bbdbd497e/env-1994-1-2-1994 [Accessed: 14 November 2024].

-CEN (The European Committee for Standardization). 2004. *CEN EN 1992-1-2:2004(MAIN) Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design* [online]. Available at: https://standards.iteh.ai/catalog/standards/cen/597bff7e-4f49-446f-ac9b-69829a09d098/en-1992-1-2-2004 [Accessed: 14 November 2024].

Chaves, I.A., Beck, A.T. & Malite, M. 2010. Reliability-based evaluation of design guidelines for cold-formed steel-concrete composite beams. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 32(5), pp.442-449. Available at: https://doi.org/10.1590/S1678-58782010000500003.

Chiorean, C.G. & Buru, S.M. 2017. Practical nonlinear inelastic analysis method of composite steel-concrete beams with partial composite action. *Engineering Structures*, 134, pp.74-106. Available at: https://doi.org/10.1016/j.engstruct.2016.12.017.

Daanoune, N., Kernou, N., Fellah, M. & El-Hiti, G.A. 2024. Reliability and mechanical performance of timber-concrete composite beams in the non-linear domain. *Građevinar,* 76(11), pp.993-1003. Available at: https://doi.org/10.14256/JCE.4055.2024.

-Dassault Systèmes. 2016. *Abaqus analysis user's guide*. Dassault Systèmes, SIMULIA.

Du, H., Hu, X., Shi, D. & Xue, W. 2021. Flexural Performance of Composite Beams Using High-Strength Steel and High-Strength Concrete. *International Journal of Steel Structures,* 22, pp.27-41. Available at: https://doi.org/10.1007/s13296-021-00558-y.

Ellingwood, B., MacGregor, J.G., Galambos, T.V. & Cornell, C.A. 1982. Probability Based Load Criteria: Load Factors and Load Combinations. *Journal of the Structural Division*, 108(5), pp.978-997. Available at: https://doi.org/10.1061/JSDEAG.0005959.

-fib (The International Federation for Structural Concrete). 2013. *fib Model Code for Concrete Structures 2010*. International Federation for Structural Concrete (fib). Available at: https://doi.org/10.1002/9783433604090.

Grandhi, R.V. & Wang, L. 1999. *Structural Reliability Analysis and Optimization: Use of Approximations.* NASA/CR-1999-209154. Document ID:19990049421 [online]. Available at: https://ntrs.nasa.gov/citations/19990049421 [Accessed: 14 November 2024].

Guo, Y.-T., Chen, J., Nie, X., Tao, M.-X., Wang, J.-J. & Fan, J.-S. 2020. Investigation of the shear resistances of steel–concrete–steel composite structures with bidirectional webs. *Journal of Constructional Steel Research*, 164, art.number:105846. Available at: https://doi.org/10.1016/j.jcsr.2019.105846.

Haldar, A. & Mahadevan, S. 1999. *Probability, Reliability, and Statistical Methods in Engineering Design*. Wiley. ISBN: 978-0-471-33119-3.

Hognestad, E. 1951. *A study of combined bending and axial load in reinforced concrete members*. University of Illinois Engineering Experiment Station: Bulletin Series No. 399.

Johnson, R.P. 2018. *Composite Structures of Steel and Concrete: Beams, Slabs, Columns and Frames for Buildings*. Wiley. Available at: https://doi.org/10.1002/9781119401353.

Liang, Q.Q. 2018. *Analysis and design of steel and composite structures, 1st Edition*. CRC Press. Available at: https://doi.org/10.1201/9781315274843.

Luo, Y., Li, A. & Kang, Z. 2012. Parametric study of bonded steel–concrete composite beams by using finite element analysis. *Engineering Structures*, 34, pp.40-51. Available at: https://doi.org/10.1016/j.engstruct.2011.08.036.

Lydia, M. & Nassim, K. 2022. Reliability Analysis and Comparative Study of Ordinary Concrete and High Performance Concrete Filled with Steel Tube under Axial Compression. *International Journal of Engineering Research in Africa*, 61, pp.245-261. Available at: https://doi.org/10.4028/p-9h1zq6.

Mamuda, A., Abubakar, I. & Samson, D. 2018. Reliability-Based Structural Safety Evaluation of Concrete-Steel Composite Beams According to Euro Code 4. *Engineering Physics*, 2(2), pp.32-40 [online]. Available at: https://www.sciencepublishinggroup.com/article/10.11648/j.ep.20180202.11 [Accessed: 14 November 2024].

Mans, P., Yakel, A.J. & Azizinamini, A. 2001. Full-Scale Testing of Composite Plate Girders Constructed Using 485-MPa High-Performance Steel. *Journal of Bridge Engineering*, 6(6), pp.598-604. Available at: https://doi.org/10.1061/(ASCE)1084-0702(2001)6:6(598).

Morse, L., Khodaei, Z.S. & Aliabadi, M.H. 2017. Multi-Fidelity Modeling-Based Structural Reliability Analysis with the Boundary Element Method. *Journal of Multiscale Modelling*, 8(03n04), art.number:1740001. Available at: https://doi.org/10.1142/S1756973717400017.

Nie, J., Li, H. & Tang, L. 2009. Experimental study on HSS-concrete composite beams. *Journal of Building Structures*, 30(02), pp.64-69 [online]. Available at: http://www.jzjgxb.com/EN/Y2009/V30/I02/64 [Accessed: 14 November 2024].

Rackwitz, R. 2001. Reliability analysis—a review and some perspectives. *Structural Safety*, 23(4), pp.365-395. Available at: https://doi.org/10.1016/S0167-4730(02)00009-7.

Rezaie, F., Farnam, S.M. & Pour Bahar, S. 2022. Numerical Analysis of Reinforced Concrete Beam-Column Joints without Transverse Reinforcement. *Numerical Methods in Civil Engineering*, 7(2), pp.50-60. Available at: https://doi.org/10.52547/nmce.2022.238.

-The Government of the Hong Kong Special Administrative Region: Buildings Department. 2020. *Code of Practice for Structural Use of Concrete 2013 (2020 Edition).* The Government of the Hong Kong Special Administrative Region: Buildings Department [online]. Available at: https://www.bd.gov.hk/doc/en/resources/codes-and-references/code-and-design-manuals/CoP_SUC2013e.pdf [Accessed: 14 November 2024].

Youn, S.-G., Bae, D. & Kim, Y.-J. 2011. Ultimate Flexural Strength of Hybrid Composite Girders Using High-Performance Steel of HSB600 at Sagging Bending. In: *Composite Construction in Steel and Concrete VI,* pp.680-690. Available at: https://doi.org/10.1061/41142(396)56.

Yu, B., Ning, C.-L. & Li, B. 2017. Probabilistic durability assessment of concrete structures in marine environments: Reliability and sensitivity analysis. *China Ocean Engineering*, 31(1), pp.63-73. Available at: https://doi.org/10.1007/s13344-017-0008-3.

Efecto de la resistencia a la compresión del hormigón sobre la fiabilidad y el momento plástico de vigas mixtas de acero y hormigón

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CAMPO: ingeniería mecánica, ingeniería civil
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: Este estudio investigó la influencia de la resistencia a la compresión del hormigón en la confiabilidad y el momento de resistencia plástica de las vigas compuestas de acero y hormigón. El objetivo fue evaluar el impacto de las variaciones de la resistencia del hormigón en el desempeño estructural, con especial atención al momento de resistencia plástica, que es crítico para la seguridad y la conformidad de la viga compuesta.

Métodos: Para modelar el comportamiento no lineal del hormigón, Abaqus creó un modelo numérico tridimensional que incluye un modelo de plasticidad del daño del hormigón (CDP). Se realizó un análisis de confiabilidad y se evaluó la probabilidad de falla utilizando simulaciones de Monte Carlo (MCS) y métodos de confiabilidad de primer orden (FORM) y segundo orden (SORM). La función de estado límite se determinó de acuerdo con los criterios del Eurocódigo 4 considerando la resistencia a la compresión del hormigón de 25 a 80 MPA.

Resultados: Como resultado, se encontró que la resistencia a la compresión del hormigón afecta significativamente el momento de resistencia plástica y el índice de confiabilidad de la viga compuesta. La alta resistencia del hormigón mejora el momento de resistencia plástica y el índice de confiabilidad varía según la propiedad geométrica y del material de la sección compuesta y las condiciones de carga.

Conclusión: La resistencia a la compresión del hormigón es un parámetro importante que determina las características estructurales y la seguridad de las vigas mixtas de acero y hormigón. Esto puso de relieve la necesidad de considerar la variabilidad de la resistencia del hormigón al diseñar y evaluar estructuras mixtas para garantizar el cumplimiento de los estándares de confiabilidad.

Palabras claves: viga compuesta, modelado no lineal, momento resistente plástico, análisis de confiabilidad, análisis de elementos finitos, probabilidad de falla.

Влияние прочности бетона при сжатии на надежность и момент пластического сопротивления сталебетонных композитных балок

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Резюме:

Введение/цель: В данном исследовании изучалось влияние прочности бетона при сжатии на надежность и момент пластического сопротивления сталебетонных композитных балок. Цель исследования заключалась в оценке влияния изменений прочности бетона на эксплуатационные характеристики конструкции. Особое внимание уделялось моменту пластического сопротивления, который имеет решающее значение для безопасности и прочности композитной балки.

Методы: Для моделирования нелинейного поведения бетона компания «Abaqus» создала трехмерную численную модель, включающую модель пластичности бетона при повреждении (CDP). Был проведен анализ надежности и оценка вероятности отказа с использованием моделирования по методу Монте-Карло (MCS) и методам определения надежности первого порядка (FORM) и второго порядка (SORM). Функция предельного состояния была определена в соответствии с критериями Еврокода 4 с учетом прочности бетона на сжатие от 25 до 80 МПа.

Результаты: Результаты исследования показали, что прочность бетона на сжатие существенно влияет на момент пластического сопротивления и показатель надежности композитной балки. Высокая прочность бетона повышает пластическое сопротивление, а показатель надежности варьируется в зависимости от геометрических параметров, свойств композитных материалов и условий нагружения.

Вывод: Прочность бетона на сжатие является важным параметром, определяющим конструктивные характеристики и безопасность сталебетонных композитных балок. Этот факт подчеркивает необходимость учета изменений прочности бетона при проектировании и оценке композитных конструкций для обеспечения соответствия стандартам надежности.

Ключевые слова: композитная балка, нелинейное моделирование, момент пластического сопротивления, анализ надежности, конечно-элементный анализ, вероятность отказа.

Утицај чврстоће бетона при притиску на поузданост и моменат пластичности спрегнутих челично-бетонских носача

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ОБЛАСТ: машинство, грађевинарство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У овој студији испитан је утицај чврстоће бетона при притиску на поузданост и пластични отпорни моменат спрегнутих носача од челика и бетона. Циљ је био да се процени утицај различитих чврстоћа бетона на понашање конструкције, с посебним нагласком на пластични отпорни моменат који је критичан за сигурност и испуњавање захтева за спрегнути носач.

Методе: За моделирање нелинераног понашања бетона, Абакус је креирао тродимензионални нумерички модел који обухвата модел оштећења бетона услед пластичности (Concrete Damage Plasticity –CDP model). Анализирана је поузданост, а вероватноћа отказа је процењена помоћу симулација Монте Карло (MCS), као и помоћу метода поузданости првог (FORM) и другог реда (SORM). Функција граничног стања одређена је према критеријумима Еврокода 4 узимајући у обзир чврстоћу бетона при притиску од 25 до 80 MPA.

Резултати: Показано је да чврстоћа бетона при притиску знатно утиче на пластични отпорни моменат и индекс поузданости спрегнутог носача. Висока чврстоћа бетона побољшава пластични отпорни моменат, док индекс поузданости варира зависно од својстава материјала, геометрије спрегнутог пресека, као и услова оптерећења.

Закључак: Чврстоћа бетона при притиску важан је параметар који одређује структурне карактеристике и сигурност спрегнутих носача од челика и бетона. Зато је при пројектовању и процени спрегнутих конструкција неопходно да се варијабилност чврстоће бетона узме у обзир како би се осигурало поштовање стандарда поузданости.

Кључне речи: спрегнути носач, нелинеарно моделирање, пластични отпорни моменат, анализа поузданости, анализа коначних елемената, вероватноћа отказа.

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