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FAILURE OF SLENDER CONCRETE COLUMNS DUE TO A LOSS OF STABILITY

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Abstract

The European standard for the design of concrete structures that are likely to lose stability requires taking into account the effects of second order theory. This effect increases the impact of a bending moment due to member deformation and additional eccentricity. Slender members can be calculated by the use of a non-linear method. This approach shows a deficit in global reliability for cases where the concrete columns fail due to the loss of stability before reaching the design resistance in the critical cross-sections. Buckling is a brittle failure which occurs without any warning, and the probability of its formation is markedly influenced by the slenderness of the column. Here, the calculation results are presented and compared with the results from an experiment which was carried out in cooperation with STRABAG Bratislava LTD at the Central Laboratory of the Faculty of Civil Engineering SUT in Bratislava. The columns were designed according to the methods stated in STN EN 1992-1-1, namely, a general non-linear method. The focus of this study is to compare multiple approaches based on codes used in Germany (DIN 1045-1, 2001) and Austria (ÖNORM B 4700, 2001) with the present European code mentioned above. The paper aims to compare the global reliability of slender concrete columns with variable slendernesses of 90 and 160.

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Key words

- Slender columns,
- Reliability,
- Safety factor,
- Loss of stability.

1 INTRODUCTION

The European standard for designing concrete columns offers three methods for taking second-order effects into account: a method based on nominal curvatures, a method based on nominal stiffness, and a general nonlinear method (EN 1992-1-1, 2004). The failure of the stability of slender concrete columns can occur before reaching the design resistance in the critical cross-sections. In such cases, it would be appropriate to define the partial reliability factor for the failure of stability of a compression member because the partial coefficients of the materials could not yet be applied and contribute to ensuring the overall reliability of the design. In the European standardized regulations, the recommended partial safety factor for the failure of stability can only be found in the Austrian National Annex (ÖNORM B 1992-1-1, 2011). In this study we compared the results of an experiment with the codes used in the past, namely, the Austrian ÖNORM B 4700 (2001) and German DIN 1045-1 (2001). This study modifies previous studies about probabilistic analysis (Benko et al., 2017), which are used for evaluating the global safety factor of the individual design methods offered in EN 1992. We also compared the effect of an increase in slenderness in the overall reliability of columns.

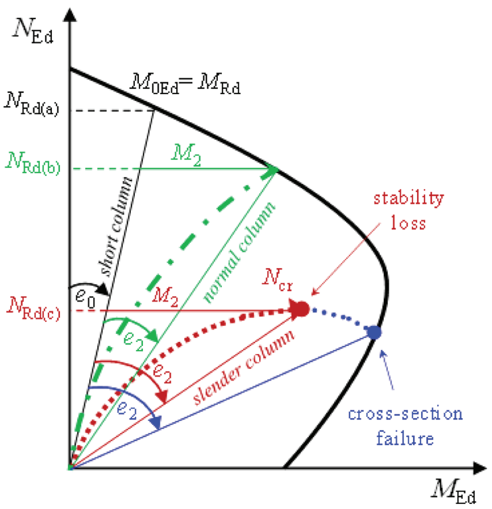


Fig. 1 *Effect of slenderness on the deformation and resistance of columns*

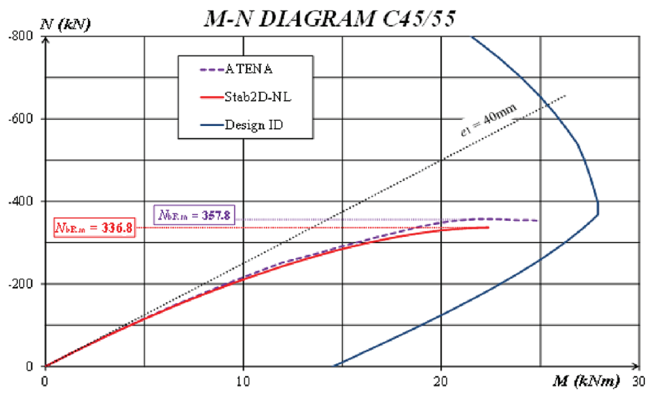


Fig. 2 *Intended normal force for the loss of stability for the first series of columns (C45/55)*

2 TEST RESULTS

2.1 Design of the test columns

The experimentally verified slender concrete columns were designed in such a way that the columns would collapse due to a loss of stability inside the interaction diagram, i.e., before achieving the design resistance in the critical cross-section with an approximate compressive strain in the concrete of εc1 = 1.5 ‰ (Benko et al., 2016). The initial eccentricity of the axial force and resistance of the columns for the failure of the stability was determined using Stab2D-NL software. The $N_{bR.m}$ value symbolizes the buckling resistance of the column analysed.

The cross-section of the column is a rectangle with dimensions of 240 x 150 mm, while the overall length of the specimens is 3840 mm. The column is reinforced with four bars with a diameter of Ø14 mm. These four bars are supplemented with another four bars with diameters of Ø14 mm and lengths of 600 mm on both ends of the columns. The supplementary bars are welded to steel plates with a thickness of 20 mm. The transverse reinforcement consists of two leg stirrups with diameters of Ø 6 mm. As the local failure on both ends can precede the collapse of the stability of the columns, the resistance is increased by doubling the transverse reinforcement along the length of the additional bars. Fig. 3 presents the geometry and reinforcement of the columns.

1.2 Tests of the materials

Thirty test samples were prefabricated during the execution of the first set (S1) of the columns. There were three prism samples of 100/100/400, six cube samples of 150/150/150, and six cylinders of 150/300 mm. The same amounts were used for the material test at the time of the experiment. An analysis of the material test results proved the intended characteristics of the C45/55 concrete and B500B steel.

1.3 Predicting the failure of columns due to a loss of stability

The use of more precise non-linear calculations is not only useful for the scientific-research domain in the laboratories of universities

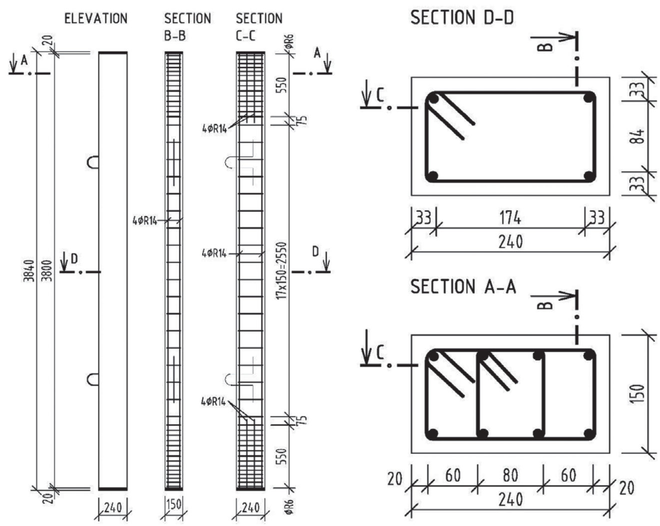


Fig. 3 *Shape and reinforcement scheme of the columns tested*

and testing institutes, but also for project offices which deal with practical design. The use of non-linear analysis for concrete members is quite difficult and requires experience when comparing the results on experimentally verified members and structures. The verification of experimental measurement results performed using non-linear methods is essential. In present conditions the options of entering input data for a non-linear analysis enables the modelling of anything. The true verification of experience and skills with non-linear analysis is possible by predicting the results of experimental measurement results before undertaking them. Therefore, we asked experts from the countries surrounding Slovakia who have experience with non-linear methods to predict the behaviour of the slender concrete columns that were prepared for testing in a laboratory of SUT in Bratislava. The results of the non-linear analysis made by experts from Slovakia, the Czech Republic, and Austria are shown in the graphs and tables below. In Table 1 and Fig. 4, the names of the experts, their workplaces, the software used, and also the value of the axial force, the deformations of the columns, and the total bending moments when the columns lose their stability are shown. The M-N diagrams show an increase in the axial force and total bending moments in the critical cross-section (the middle of the column). The maximal values of the axial force also define the instant when the column fails due to a loss of stability. The results of the various experts displayed in Fig. 4 and Table 1 are the best examples of the uncertainties that the nonlinear method brings to calculations.

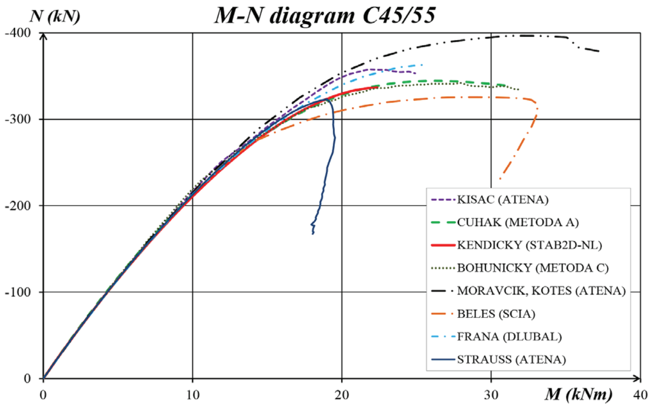


Fig. 4 *Results from the various experts for the C45/55 columns*

Tab. 1 *Comparison of results*

Company	Expert	Software	N [kN] Normal force	u_y [mm] Deformation	M [kN.m] Bending moment
STU Bratislava	Kišac M.	Aténa	357.8	20.9	21.8
STU Bratislava	Čuhák M.	Metóda A	344.4	35.5	26.0
STU Bratislava	Kendický P.	Stab2NL	336.8	26.4	22.4
Leptón s.r.o.	Bohunický B.	Metóda C	342.0	44 .0	28.0
ZU Žilina	Moravčík M. Koteš P.	Atena	396.6	38.7	31.2
Nemetschek -Scia	Beleš I.	Scia	325.5	49.4	29.1
Dlubal - CZ	Fráňa J.	Dlubal	363.0	30.3	25.5
BOKU Wien - A	Strauss A.	Atena	323.0	18.9	19.0

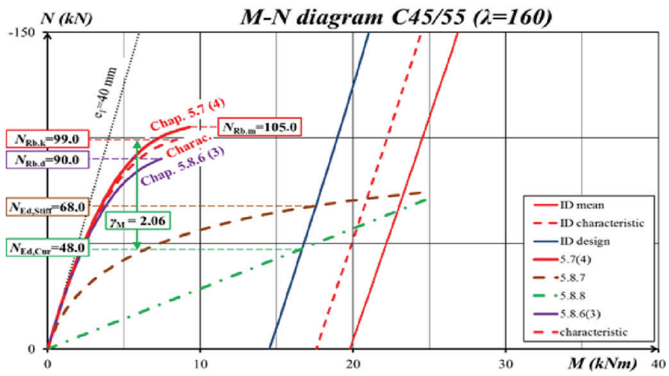
2.4 Results of the experiment

After the predictive calculations, preparation in the laboratory, and production of the experimental samples, the columns were tested at the Central Laboratory of the Faculty of Civil Engineering in Bratislava. In Fig. 5, a behaviour diagram of the slender concrete columns from Series S1 is presented. In the M-N diagram, the behaviour of the increasing normal force and global bending moment can be seen. This behaviour was observed at a critical point of the column. The ε-N diagram presents the strains caused by an increase in the normal force on both sides of the column. Other details about the experiments are described in (EN 1992-1-1, 2004). The red curve in Fig. 5 represents the results of the nonlinear calculations that were executed using SOFiSTiK. The material model for these calculations was modified to match the results of the experiments.

3 EC 2 – PARAMETRIC STUDY

The results of the parametric study are shown in Figure 6; Tables 2 and 3 show the differences in the reliability of the design methods according to Eurocode 2 for the columns with an initial eccentricity of axial force of 40 mm and a slenderness of λ=160. Table 2 contains the values for the column resistance, the partial reliability factors for the materials and the loads, as well as the overall reliability factors of the above-stated design methods.

Table 3 summarizes the values of the overall reliability factors of the slender concrete columns with an initial eccentricity of axial force of 40 mm and a slenderness of λ = 100, 120, 140 and 160. Based on Tables 2 and 3, the trend in the decreasing overall reliability of the nonlinear method used on slender concrete columns is notable.



Maximum normal force calculated by using	
NRb.m	Nonlinear method - mean material values
NRb.k	Nonlinear method - characteric material values
NRb.d	Nonlinear method - design material values
Ned.Stiff	Method of nominal stiffness
Ned.Cur	Method of nominal curvature

Fig. 6 *Results of the parametric study*

Tab. 2 *Tabulated results of the parametric study*

overall reliability			Axial force [kN]		γ_F	γ_M	γ_O
			design	characteristic	load	material	overall
-	-	characteristic	99.0	–	1.40	–	–
Section	5.8.6(3)	design	90.0	64.3	1.40	1.10	**1.54**
Section	5.8.7	stiffness	68.0	48.6	1.40	1.46	**2.04**
Section	5.8.8	curvature	48.0	34.3	1.40	2.06	**2.89**

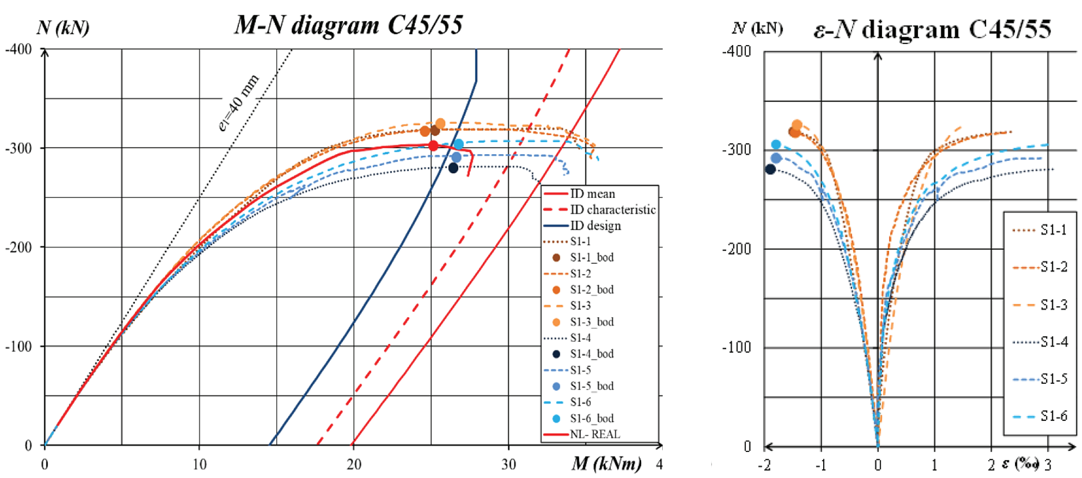


Fig. 5 *Diagram a) bending moment – normal force, b) strain (compression, tension) – normal force*

Tab. 3 *Comparison of reliability with various slenderness values*

overall reliability			slenderness λ			
			100	120	140	160
Section	5.8.6(3)	design	1.6	1.57	1.56	1.54
Section	05.08.2007	stiffness	1.89	1.97	1.99	2.04
Section	05.08.2008	curvature	2.64	2.82	2.84	2.89

4 ÖNORM B 4700

ÖNORM B 4700 is an Austrian code from 2001 that was used in Austria before the Eurocodes. ÖNORM B 4700:2001 was selected for comparison because in chapter 3.4.3.3.1, it limits nonlinear calculations for structural members that are likely to lose stability. The material characteristics for NL modelling are the values from the material test. If we did not have the results of the material tests from the experiment, the material characteristics would be set by the code (ÖNORM B 4700, 2001). The limitation for the NL calculations is a sufficient degree of safety against the system´s failure of stability, which is reached when the lead combination of the load results at the most of 80% of the column capacity for a loss of stability. This method can only be used for concrete class C45/55 or lower because it is the highest type of concrete defined in this code. The concrete in ONORM (B 60) is characterized differently than in EC (C45/55) but has the same prescribed cylindrical strength in compression. Concrete members that are made with a higher type of concrete cannot be examined or designed under this code. Based on this fact, we were not able to perform a similar comparison with the other concrete columns that were examined at the Department of Concrete Structures and Bridges of the Faculty of Civil Engineering SUT in Bratislava. The results of the calculations show a comparison of the reliabilities of the different calculation methods. This method was also used on members with different degrees of slenderness. All of the results are shown in the tables and figures below.

5 DIN 1045-1:2001

DIN 1045-1 (2001) is a German code. The nonlinear calculation method in this code is based on a completely different approach than the one in ONORM B 4700:2001. This method regulates the strength of the materials that are used in reinforced concrete. It reduces the characteristic value of the strength in compression for concrete to 72% of the original value, which matches the value in Eurocode 2. On the other hand, the modified yield strength of the steel reinforcement is increased to 110% of the original characteristic value.

$$f_{yR} = 1{,}1 \, . \, f_{yk} \tag{1}$$

$$f_{cR} = 0{,}85 \, . \, \alpha \, . \, f_{ck} \tag{2}$$

The recommended value for α is 0.85. f_{yR} is the modified yield value for the reinforcement, and f_{cR} is a modified value of the strength in compression for concrete. The material characteristics for the interaction diagram have the same values as in the Eurocode, which means they are not regulated in any way. This code either limits or increases other material properties for nonlinear calculations. It also limits prestressing, but this technology was not used in the members tested, so we are not focusing on them. All of the limitations can be found in the German code (DIN 1045-1, 2001). The design value of the normal force is calculated by a decrease in the maximal calculated normal force reached when using the material strengths f_{cR} and f_{yR} with safety factor γ_R. This safety factor has values of 1.3 for permanent and temporary design situations and of 1.1 for exceptional design situations.

6 COMPARISON OF THE RELIABILITY OF THE VARIOUS CALCULATION METHODS

The experimental tests undertaken have verified the results predicted by the authors and the behaviour of the slender columns. Some of the columns failed due to the loss of stability before reaching the resistance of the cross-sections. The failure of stability occurred inside the design interaction diagram M-N of the column's cross-section. The importance of a correct definition is enhanced by the fact of a brittle failure without warning, which requires a higher overall degree of reliability than ductile failures. The main focus of this study is to compare the results of the nonlinear calculation method in the Eurocode (EN 1992-1-1, 2004) with the methods used in ONORM B 4700 (2001) and DIN 1045-1 (2001). Fig. 7 shows a comparison between EC 2 and ONORM B 4700:2001. The differences between the current EC 2 and DIN 1045-1:2001 are displayed in Fig. 8. As these figures indicate, there are not many similarities between the currently valid EC 2 and the other codes compared in the results of the nonlinear calculations. The nonlinear calculations were performed using SOFiSTiK. The material model was modified only in the general NL method based on the EC2 (EN 1992-1-1, 2004) method. It was modified to match the results of the experiment as is shown in Fig. 5.

Based on Figs. 7 and 8, and Table 4, we can see a significant difference between the currently valid Eurocode and the codes compared with it. The reliability of ONORM B 4700 and DIN 1045-1 is surprisingly similar. This similarity was achieved with the characteristic values of the axial stress. The material properties of the calculations for the nonlinear model were not the same. These similar results were calculated using completely different calculation methods and material properties prescribed in the codes. The differences based on the different calculation approaches are notable in the design values of the axial forces. As previously shown, the parametric study displays a decrease in reliability (for the nonlinear calculations in EC 2) with an increase in the column´s slenderness. Based on this information we performed another comparison with the code used in the past.

The results of the calculation method in ONORM B 4700 are displayed in Fig. 9 and Table 5. We can see a decrease in the overall reliability of the currently valid calculation method in EC 2. On the other hand, the results of the overall reliability of ONORM B 4700 are almost the same. That is not surprising, because this calculation

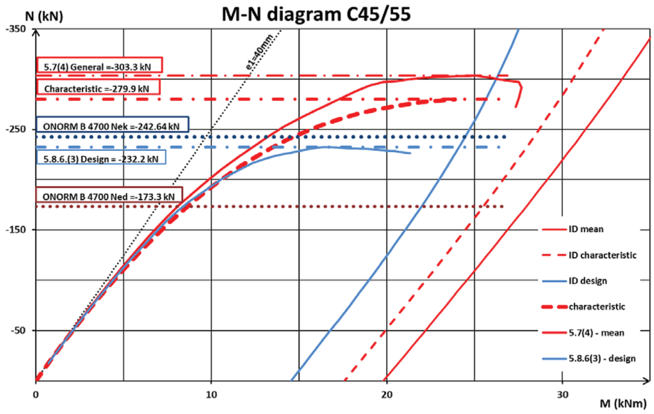


Fig. 7 *Comparison of the different calculation methods EC 2 – DIN 1045-1:2001*

Tab. 4 *Comparison of the different calculation methods and experimental results*

overall reliability of collumns with Slenderness **λ=89** to the characteristic values of material properties		Material parameters	Axial force (kN)		γ F	γ M	γ O
			design	character.	load	material	overall
-	-	character.	-279.9	-199.9	1.4	1.00	**1.40**
EC 2	5.8.6 (3)	design	-232.2	-165.9	1.4	1.21	**1.69**
ONORM B 4700	3.4.3.3.1	character.	-242.64	-173.3	1.4	1.15	**1.61**
ONORM B 4700	3.4.3.3.1	design	-173.3	-123.8	1.4	1.62	**2.26**
DIN 1045-1	3.4.3.3.1	_	-244	-174.3	1.4	1.15	**1.61**
DIN 1045-1	3.4.3.3.1	design	-186.7	-133.4	1.4	1.50	**2.10**

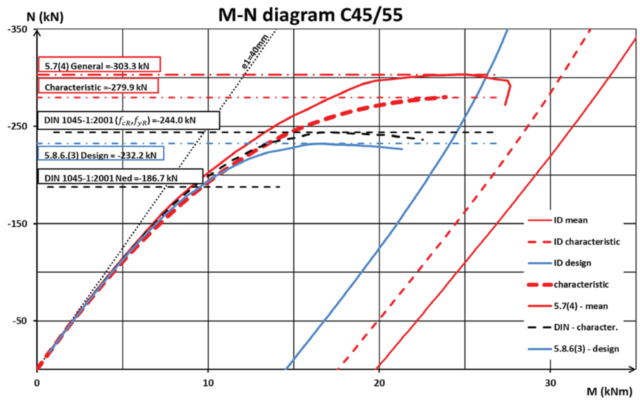


Fig. 8 *Comparison of the different calculation methods EC 2 – ONORM B 4700:2001 – slenderness λ=160*

method is based on the limitation of the results. The slenderness of the column does not have any effect on the reliability of the method located in this code. The results based on the calculation method in DIN 1045-1 are displayed in Fig. 10 and Table 5. The overall reliability of this method decreased with higher degrees of slenderness, which is not surprising because it limits the material parameters entered in the nonlinear calculations. The overall reliability of this method is also lower that the calculation method used in the Austrian method and has greater differences in reliability for concrete members with higher degrees of slenderness.

7 CONCLUSIONS

The results of the nonlinear calculations show different overall levels of reliability of the design values calculated by the different methods prescribed in the ONORM B 4700 and DIN 1045-1. An analytical study was performed with a slenderness of columns λ= 89 and

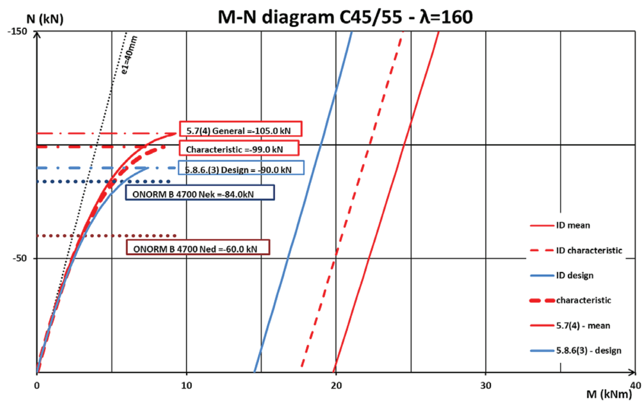


Fig. 9 *Comparison of the different calculation methods EC 2 – DIN 1045-1:2001 – slenderness λ=160*

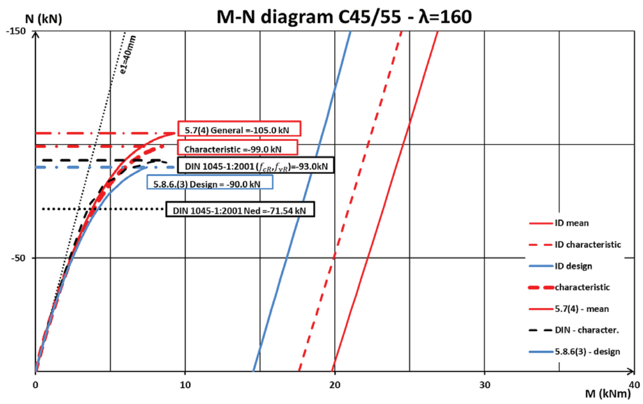


Fig. 10 *Comparison of the different calculation methods EC 2 – DIN 1045-1:2001 – slenderness λ=160*

Tab. 5 *Comparison of the different calculation methods for slenderness λ=160*

overall reliability of collumns with slenderness **λ=160** to the characteristic values of material properties		Material parameters	Axial force (kN)		γ F	γ M	γ O
			design	character.	load	material	overall
-	-	character.	-99	-70.7	1.4	1.00	**1.40**
EC 2	5.8.6 (3)	design	-90	-64.3	1.4	1.10	**1.54**
ONORM B 4700	3.4.3.3.1	character.	-84	-60.0	1.4	1.18	**1.65**
ONORM B 4700	3.4.3.3.1	design	-60	-42.9	1.4	1.65	**2.31**
DIN 1045-1	3.4.3.3.1	_	-93	-66.4	1.4	1.06	**1.49**
DIN 1045-1	3.4.3.3.1	design	-71.54	-51.1	1.4	1.38	**1.94**

λ= 160. The highest overall degree of reliability of the concrete members that are likely to lose stability was obtained by ONORM B 4700 in all the slenderness cases that we examined (2.26 for λ= 89, 2.31 for λ= 160). On the other hand, the lowest overall degree of reliability (1.4) was shown in the columns that are designed according to the currently valid Eurocode 2. The reliability of the German code (2.1 for λ= 89, 1.91 for λ= 160) is exactly in the middle of the calculation methods tested. A decrease of reliability is noticeable in EC 2 and also in DIN 1045-1. This trend proves the conclusions of previous papers (Benko et al., 2016; 2017) that point out a significant decrease in the overall reliability with a higher degree of slenderness. All of the RC columns analysed failed due to a loss of stability in their design interaction diagram.

The nonlinear calculations were not deterministic. The results of the deformation of the columns subjected to axial force with or without bending depend on the user´s experience. The differences in the results between users can be very large and, in some cases, could have a greater impact on the results than the partial safety factors on the load site. In cases where a column subjected to axial force loses stability before the critical cross section reaches its resistance, the partial coefficient on the material side is also lost in the calculations.

It is proposed that CEN 250 SC2 reassess the use of the non-linear method according to (EN 1992-1-1, 2001) Chap.5.8.6 (Benko et al., 2016) for elements subjected to axial force. We also recommend the non-linear method for compressed elements only for the assessment of existing structures. In any case the partial coefficient for the loss of stability should be defined (EN 1992-1-1, 2001) before reaching the critical cross-sectional resistance at the material characteristic level as it is in the Austrian NAD (ÖNORM B 1992-1-1, 2011).

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