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QUALITY CONTROL & NUMERICAL NONLINEAR MATERIAL MODELLING FOR THE LOAD-BEARING CAPACITY OF SLENDER REINFORCED CONCRETE COLUMNS – COMPARISON OF SAFETY FORMATS

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Abstract: Modern codes allow advanced nonlinear formats to calculate the bearing-buckling capacity of slender reinforced concrete column elements. In a previous part of this paper series, investigations of a priori collaborative Round-Robin tests of numerical simulations showed that the load capacity of slender single columns obtained by Nonlinear Finite Element Methods (NLFEM) is significantly overestimated when compared to experimental values. On the other side, the simplified formats adopted by design codes (e.g. nominal curvature-based method) provide too conservative results concerning the experimental derived bearing buckling capacity. The investigations are divided into two parts. Part I considers the experiments' findings and the nonlinear modelling. Part II aims twofold: (i) provide a quantitative comparison of the Eurocode column design rules with the international design regulations from the USA, China, Japan, and Canada concerning the safety and design format and (ii) identify possible strengths and weaknesses in the different approaches.

1 INTRODUCTION

The methods detailed in Part I of this paper series, were subsequently applied to the tested slender columns with the aims of (a) comparing the code-specific methods with each other and (b) evaluating the safety margin of the code-based results to those obtained experimentally.

2 EN 1992-1-1 SAFETY FORMATS

Recently, experts have expressed very high interest in analyzing the verification methods permitted in the Eurocodes for determining the load-bearing capacity of slender columns. However, there is some doubt that the existing safety of columns can be correctly described by the Eurocode verification procedures, which are based solely on the partial safety factors of the material γ_M and load γ_F. Therefore, the partial safety factors of the material γ_M and the global partial safety factors γ_0 (see Table 1) can be determined from equation (1).

The four Eurocode verification procedures for slender columns are analyzed using the results of the laboratory-tested columns ($\lambda = 89$, $e_1 = 40$ mm) [1] as reference values. At the same time, details of the material properties are provided in [2]. In these analyses, a partial safety factor of γ_F = 1.4 is assumed for the loading side, as shown in Table 1.

$$\gamma_0 = \gamma_F \cdot N_{Rk} / N_{Ed} = \gamma_F \cdot \gamma_M \qquad (1)$$

The *N-M* gradients, as illustrated in Figure 1, help in identifying the relations between the numerical formats and testing results; in particular, Figure 1 shows the *N-M* gradients obtained from:

a) the column tests S1-1 to S1-6 made of concrete C45/55 carried out in the laboratory of the University Bratislava [1] (black dashed lines in Figure 1),
b) the nonlinear analysis according to EN 1992-1-1, Chapter 5.7 (4) '**general method**' (solid red line in Figure 1),
c) the non-linear analysis according to EN 1992-1-1, Chapter 5.8.6 (3) '**general method**' (purple solid line),
d) the analysis according to EN 1992-1-1, Chapter 5.8.7 '**nominal stiffness procedure**' (brown dashed lower line),
e) the analysis according to EN 1992-1-1, Chapter 5.8.8 '**nominal curvature procedure**' (green dashed-dotted lower line).

Further, the *N-M* gradients determined experimentally, analytically and numerically can be related to the Eurocode interaction diagrams (I-D). The I-D can also be differentiated regarding design, characteristics and mean level, see Figure 1. The intersections of the *N-M* gradients with the I-D interaction curves provide essential information for determining the partial safety factors associated with the material properties and the global safety factors γ_0, as shown in Table 1.

In a further step, the partial safety factors of the material's resistance side γ_M (partial safety factors of the material) and the global partial safety factors γ_0 for the above-mentioned methods can be determined by the following simplified ratio considerations. In particular, the global partial safety factor γ_0 makes it possible to show a first approximation of the strong fluctuations in the safety of the EN 1992-1-1 verification formats.

In a technical sense, the global safety factor γ_0 is determined by multiplying γ_F by γ_M and corresponds to a classic semi-probabilistic approach at the cross-sectional level that is also included in the current EN1992-1-1 verification format for columns. For example, a γ_F = 1.40 and γ_M = 1.34, which are concrete, specific factors, result in a global safety factor of γ_{0_ref} = 1.88, which is subsequently used as a reference value, see Table 1.

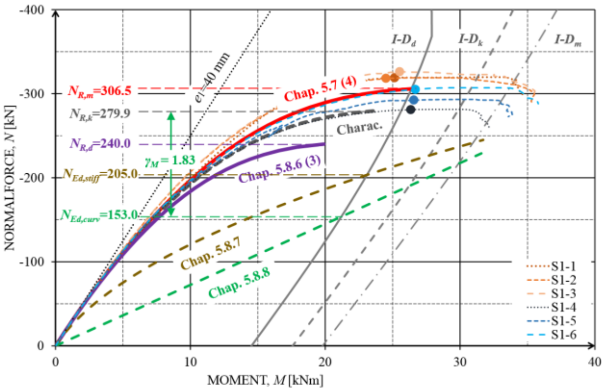


Figure 1: *N-M* gradients determined experimentally, analytically and numerically according to EN1992-1-1 verification procedures with respect to the I-D (I-D_d = on design value level, I-D_k = on characteristic value level, I-D_m = on mean value level) for column characteristics λ = 89, e_1 = 40 mm made of C45/55 [1].

Based on the characteristic load-bearing capacity N_{Rk} = 279.9 kN determined from the experimental column tests, these investigations show considerable differences in the safety levels of the EN 1992-1-1 verification formats, as seen in Table 1. In particular, according to EN1992-1-1 Chapter 5.8.6 (3), the permitted nonlinear numerical analysis method results in a significant undercut of the reference value $\gamma_{0,ref}$ = 1.88. Among other things, these observations motivated the subsequent detailed analysis of the Eurocode interaction diagrams (I-D) and the associated *N-M* gradients according to EN 1992-1-1 and the *N-M* gradients according to the standards of the USA, China, Japan and Canada. Further details are provided in the following sections.

The I-D can be developed using fundamental physics from the column's geometrical and material properties.

Table 1: Global and partial safety factors of the loading and resistance of columns with a slenderness λ = 89 and an initial eccentricity e_1 = 40 mm made of C45/55 computed for the EN 1992-1-1 verification procedures and concerning the laboratory-tested columns [1]

N_{Rd} [kN]	N_{Rk} [kN]	γ_F	γ_M	γ_0
-	279.9	1.40	1.00	**1.40**[a]
N_{Ed} [kN]	N_{Ek} [kN]	γ_F	γ_M	γ_0
240.0	171.4	1.40	1.17	**1.64**[b]
205.0	145.0	1.40	1.38	**1.93**[c]
153.0	109.3	1.40	1.83	**2.56**[d]
		Cross-section safety factor format		
		γ_F	γ_M	γ_0
		1.40	1.34	**1.88**

see Figure 1. a) black dashed line, from laboratory tests; b) purple solid line, from EN 1992-1-1, Chap. 5.8.6(3); c) brown dashed line, from EN1992-1-1, Chap. 5.8.7; d) green dashed line, from EN 1992-1-1, Chap. 5.8.8; γ_F …load partial safety factor; γ_M …material partial safety factor; γ_0…global partial safety factor

A distinction can also be made in the mean value level I-D$_m$, characteristic level I-D$_k$ or design level I-D$_d$. Nevertheless, as presented in the code regulations such as EN 1992-1-1, a consistent verification method should provide the maxima of the associated *N-M* gradients on the I-D lines or to the right of it, see Figure 1. However, as can be seen from this figure:

a) The *N-M* gradients of the column tests, which have to be considered as mean value results, have their maximum on the left side of I-D$_m$, which indicates a clear I-D$_m$ non-compliant stability failure,

b) the *N-M* gradients of the nonlinear analysis derived according to the EN 1992-1-1, Chapter 5.7(4) 'general method procedure' (solid red line), which also have to be considered as mean value results, have their maximum on the left side of I-D$_m$ which consequently also indicates a clear I-D$_m$ non-compliant stability failure,

c) the *N-M* gradients of the nonlinear analysis derived according to the EN 1992-1-1, Chapter 5.8.6(3) 'general method procedure' (purple line), which have to be considered as design value results, have their maximum on the left side of I-D$_d$, which also indicates an apparent I-D$_d$ non-compliant stability failure,

d) the *N-M* gradients of the two simplified 'nominal stiffness procedure' and 'nominal curvature procedure' meet the criterion of the I-D$_d$.

3. SAFETY FORMAT COMPARISON

3.1 Investigated slender columns Safety format comparison concerning the Eurocode I-D

As it has been shown that the I-D diagrams of the individual participating countries differ significantly from each other, the comparison of the safety formats focuses on the country-specific *N-M* gradients for the Eurocode I-D's. Therefore, the safety formats were detailed by comparing the country-specific margin probability distribution functions (PDF$_{country}$) on the normal-force axis with the probability distribution functions obtained from the experiments (PDF$_{exp}$). The following process steps were carried out to determine the PDF$_{country}$ in compliance with the Eurocode I-D's, see Figure 2:

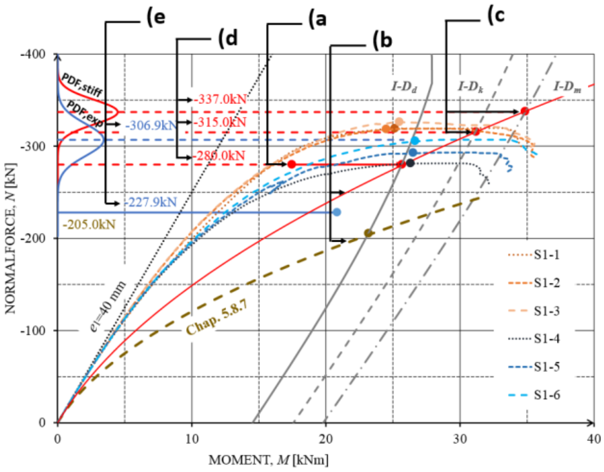


Figure 2: Determination process of the PDFcountry and PDF$_{exp}$ in compliance with the Eurocode I-D's for the comparison of the safety formats.

a) The design level failure axial forces N_{Ed} and moments M_{Ed} provided by each partner during the Round-Robin Tests [32] were projected to the Eurocode I-D$_d$ by adjusting the moment component,

b) an adapted *N-M* gradient analogous to the one of EN 1992-1-1 Chapter 5.8.7 'nominal stiffness procedure' has been created for the country-specific data by passing it through the new (N_{Ed} $M_{Ed'}$) point made on Eurocode I-D$_d$, see Figure 2,

c) the failure axial forces at the characteristic level N_{Ek} and at the mean level N_{Em} were generated by intersecting the adapted *N-M* gradient with the Eurocode I-D$_k$ and I-D$_m$,

d) in consequence, the descriptive statistical quantities N_{Ed}, N_{Ek} and N_{Em} of the failure axial forces on the action side were used to generate the PDF$_{country}$ on the axial force axis of the country-specific method in combination with the Eurocode I-D's,

e) the descriptive statistical quantities $N_{Ed,exp}$, $N_{Ek,exp}$ and $N_{Em,exp}$ of the axial failure force obtained from the experimental column tests were determined according to Table 2. Subsequently, the PDF$_{exp}$ on the axial force axis was generated using the aforementioned statistical quantities,

f) based on the determined PDF$_{country}$ and PDF$_{exp}$, the deviations in the mean values and standard deviations were determined according to Table 2, last column.

The I-D plays a central role in assessing the safety and partial safety factors, and it allows an assessment of whether the verification formats are inherently consistent. This is not the case, as demonstrated by the EN 1992-1-1 nonlinear analysis procedures. In addition, the I-D allows the development of PDFs to verify code formats. Suppose one considers, for example, the nominal stiffness *N-M* gradient shown in Figure 3 (brown dashed lower line). In that case, we obtain the axial forces at the design, characteristic and mean value level, see Table 2. These descriptive statistical quantities allow the development of the normal PDF$_{stiff}$ margin distribution and its comparison with the PDF$_{exp}$ margin distribution and a subsequent safety assessment.

Table 2: Safety format comparison between the nominal stiffness format associated margin PDF$_{stiff}$ and the experiments associated margin PDF$_{exp}$ of the tested columns ($\lambda = 89$, $e_1 = 40$ mm made of C45/55), see Figure 3.

EN1992-1-1, Chapter 5.8.8 **'nominal stiffness procedure'**					
Design Value Level ①		Characteristic Value Level ②		Mean Value Level ③	
N_d [kN]	M_d [kNm]	N_k [kN]	M_k [kNm]	N_m [kN]	M_m [kNm]
205.0	24.28	227.00	29.80	244.00	32.80

Laboratory **column tests** [1]		**Safety analyses** of PDF$_{stiff}$ to PDF$_{exp}$	
Mean Value Level ④	Design Value Level ⑤	$E = (1 - PDF_{stiff} / PDF_{exp})$	
N_m [kN]	N_d [kN]	mean [%]	standard deviation [%]
309.8	227.98	21.24 (smaller)	52.4 (smaller)

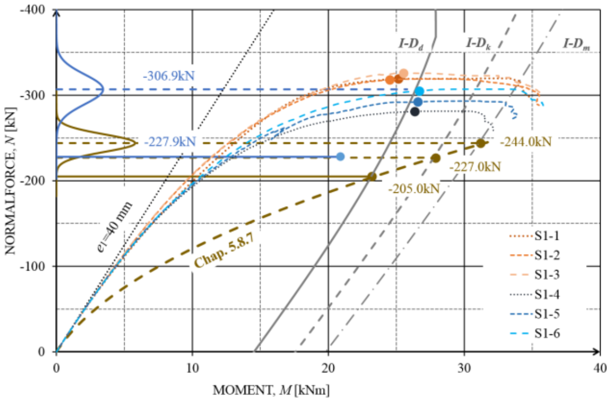


Figure 3: Safety format comparison procedure between the EN 1992-1-1 nominal stiffness format associated margin PDF$_{stiff}$ and the experimental margin PDF$_{exp}$ of the tested columns ($\lambda = 89$, $e_1 = 40$ mm made of C45/55), see also Table 2

The mean value of the PDF$_{exp}$ from the laboratory column tests at the intersection with the I-D$_m$ was determined with $N_{m,exp}$ = 309.80 kN and the $N_{d,exp}$ = 227.98 kN. Comparing the customarily distributed PDF$_{exp}$ in the axial force with the considered PDF$_{stiff}$ of the 'nominal stiffness format' shows a significant deviation, as can be seen in Figure 3 and Table 2, whereby the PDF$_{stiff}$ is below the PDF$_{exp}$ on the conservative, safe side. These considerations can also be carried out for the marginal distributions on the moment axis, as seen in Table 2, whereby these analyses, in this case, were dispersed due to the dominant role of the axial force.

3.1 Chinese verification format concerning the Eurocode I-D lines

According to the Chinese standards, the analyses show, as seen in Table 3, a maximum axial force of 282.33 kN at 40 mm eccentricity, which is close to the initial value of the initial capacity according to the experimental results in Table 1. In addition, the Chinese verification format was also carried out for an eccentricity e_1 = 30 mm and 25 mm as part of the Round-Robin Modelling campaign [1], as seen in Table 3. This variation allows an insight into the sensitivity of the support load on the introductory load point.

Table 3: Computed load-bearing capacity according to the Chinese verification formats load capacity for the investigated slender columns (λ = 89, and initial eccentricity e_1 = 40 mm, 30 mm and 25 mm) made of concrete C45/55.

Bearing capacity of Chinese verification format					
e_1=40 *mm*		e_1=30 *mm*		e_1=25 *mm*	
N_d [kN]	M_d [kNm]	N_d [kN]	M_d [kNm]	N_d [kN]	M_d [kNm]
282.33	13.09	330.61	12.50	375.92	12.09

Laboratory column tests [1] N_m = 309.80 kN

It was noticeable in the case of the values shown in Table 3 that the moment component is minimal. Therefore, in the first step, the computed load-bearing capacities according to the Chinese verification formats ($N_{Ed,china}$ = 282.33 kN, $M_{Ed,china}$ = 13.09 kNm, see Table 3) were projected onto the Eurocode I-D's according to sec. 3.1. The Chinese *N-M* gradient curve adjusted according to chapter 5.2, solid red line Figure 4 provides the axial forces at the design, characteristic and mean value level, see Figure 4. These descriptive statistical quantities are used in sec. 3.1 to derive the PDF$_{\text{china}}$ margin distribution of the China verification format, process the comparison with the PDF$_{\text{exp}}$ margin distribution, and perform a subsequent safety assessment. The determination of the PDF$_{\text{exp}}$ based on the laboratory test results has already been discussed in Part I. Finally, the comparison of the normally distributed PDF$_{\text{exp}}$ in the axial force with the considered PDF$_{\text{china}}$ of the 'Chinese verification format' shows a significant deviation, as can be seen in Figure 4 and in Table 4, whereby the PDF$_{\text{china}}$ is above the PDF$_{\text{exp}}$ on the risky / unsafe side. These considerations are also performed for the moment axis's marginal distributions, as seen in Table 4.

Table 4: Safety format comparison between the Chinese verification format associated margin PDF$_{\text{china}}$ and the experiments associated margin PDF$_{\text{exp}}$ of the tested columns (λ = 89, e_1 = 40 mm made of C45/55), see Figure 4.

'Chinese verification format'					
Design Value Level ①		Characteristic Value Level ②		Mean Value Level ③	
N_d [kN]	M_d [kNm]	N_k [kN]	M_k [kNm]	N_m [kN]	M_m [kNm]
282.33	13.09	318.00	32.50	340.00	36.00

Laboratory **column tests** [1]		**Safety analyses** of PDF$_{stiff}$ to PDF$_{exp}$	
Mean Value Level ④	Design Value Level ⑤	E = (1 - PDF$_{stiff}$ /PDF$_{exp}$)	
N_m [kN]	N_d [kN]	mean [%]	standard deviation [%]
309.8	227.98	-9.74 (higher)	29.27 (smaller)

It can be seen from Table 4 that when comparing the blue and red PDFs of Figure 4, the deviation of the Chinese standard method compared to the mean value from the experimental results is not that significant, with -9.74 % and would be on the unsafe side - the method doesn't match so well with the experimental values on the interaction front. The projection of the axial force on the interaction curve of the Eurocode would significantly increase the moment. This significant deviation in the interaction curves should be the subject of further studies. However, the variations of 29.27% in the standard deviation are substantial and beyond an acceptable range.

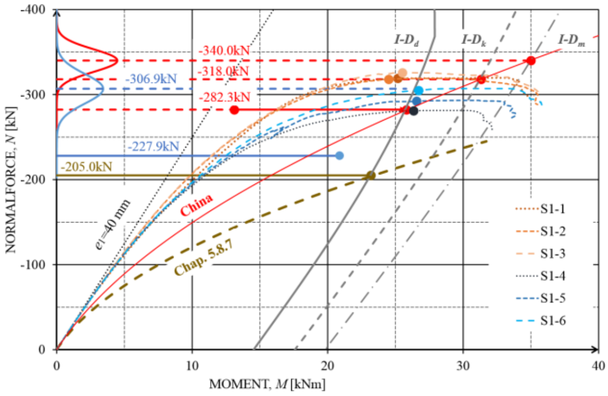


Figure 4: Safety format comparison procedure between the 'Chinese verification format' associated margin PDF_{stiff} and the experimental margin PDF_{exp} of the tested columns ($\lambda = 89$, $e_1 = 40$ mm made of C45/55), see also Table 4.

3.2 Japanese verification format concerning the Eurocode I-D lines

the Japanese design code method does not allow the construction of slender columns due to the high local seismicity. Hence the procedure of comparing the codes using the Eurocode interaction diagram, as shown in above, makes no sense and would only be of limited meaning. The verification in the Japanese Design Code focuses on the cross-sectional level. It would result in an axial force of 580 kN at the design level for the column cross-section of the investigated columns.

3.3 American verification format concerning the Eurocode I-D lines

In the same context, the 'American verification format' has been compared to the experimental test results, as shown in Figure 5. The 'American verification format' results PDF_{US} were analyzed in the previously presented manner. The respective values are presented in Columns ①-③ of Table 5 and correspond to the blue and red PDFs of Figure 5. Table 5 shows that the deviation of the 'American verification format' PDF_{US} from the experimental results PDF_{exp} in terms of mean values is not that significant with -8.78% and would be on the unsafe side. The projection of the axial force on the Eurocode I-D line increases at the moment. This deviation in the I-D lines should therefore be the subject of further studies. The differences in the standard deviations of 30.48% can be assessed as significant.

Table 5: Safety format comparison between the American verification format associated margin PDF_{china} and the experiments associated margin PDF_{exp} of the tested columns ($\lambda = 89$, $e_1 = 40$ mm made of C45/55), see Figure 5.

'American verification format'					
Design Value Level ①		Characteristic Value Level ②		Mean Value Level ③	
N_d [kN]	M_d [kNm]	N_k [kN]	M_k [kNm]	N_m [kN]	M_m [kNm]
280.00	26.00	315.00	32.60	337.00	36.20

Laboratory **column tests** [1]		**Safety analyses** of PDF_{stiff} to PDF_{exp}	
Mean Value Level ④	Design Value Level ⑤	E = (1 - PDF_{stiff} /PDF_{exp})	
N_m [kN]	N_d [kN]	mean [%]	standard deviation [%]
309.8	227.98	-8.78 (higher)	30.48 (smaller)

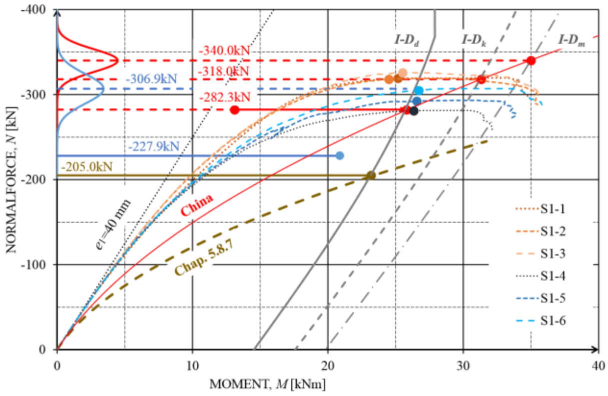


Figure 5: Safety format comparison procedure between the 'American verification format' associated margin PDF_{stiff} and the experimental margin PDF_{exp} of the tested columns ($\lambda = 89$, $e_1 = 40$ mm made of C45/55), see also Table 5

About the previously defined Eurocode I-D lines used for the verification, it is crucial to recognize that the I-D's partly made available by the partners differed significantly. Figure 6, for example, shows this discrepancy between the American verification I-D lines and the Eurocode I-D lines. Since these diagrams are based on a clearly defined physical basis, urgent analysis is required here to determine the cause or causes of these deviations.

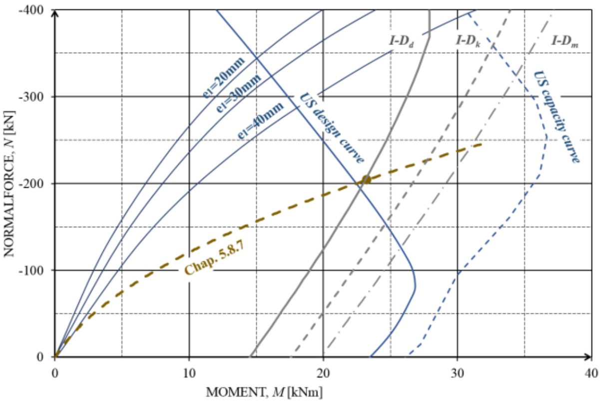


Figure 6: *N-M* gradients of the 'American verification format' vs the Eurocode and US I-D lines of the tested columns (λ = 89, e_1 = 40 mm made of C45/55).

3.4 Canadian verification format concerning the Eurocode I-D lines

The Canadian verification format exhibits similar outcomes to the American verification format, with the same mean maximum axial force and standard deviation and the same global resistance factor and normal design force (see Figure 7). Nonetheless, the bending moments corresponding to the maximum axial forces differ slightly from the US design format. The mean of these bending moments is close to the experimental mean one (-8.78 %). In other words, the Canadian verification format, as well as the American verification format, are very sensitive to material and geometric uncertainties. The interaction points are presented in Columns ①-③ of Table 6.

Comparing the blue and red PDFs of Figure 7 allows us to quantitatively assess the code format concerning the experimental results, as in Table 6. The deviation of the mean value of the Canadian verification format from the experimental results is not that significant, with -8.87% and would be on the unsafe side. However, the projection of the axial force on the Eurocode I-D lines results in a considerable increase at the moment. Therefore, this significant deviation in the interaction curves should be investigated further. In addition, the standard deviations differ significantly (30.48%).

Table 6: Safety format comparison between the Canadian verification format associated margin PDF_{china} and the experiments associated margin PDF_{exp} of the tested columns (λ = 89, e_1 = 40 mm made of C45/55), see Figure 7.

'Canadian verification format'					
Design Value Level ①		Characteristic Value Level ②		Mean Value Level ③	
N_d [kN]	M_d [kNm]	N_k [kN]	M_k [kNm]	N_m [kN]	M_m [kNm]
280.00	17.50	315.00	32.60	337.00	36.20

Laboratory **column tests** [1]		**Safety analyses** of PDF_{stiff} to PDF_{exp}	
Mean Value Level ④	Design Value Level ⑤	$E = (1 - PDF_{stiff} / PDF_{exp})$	
N_m [kN]	N_d [kN]	mean [%]	standard deviation [%]
309.8	227.98	-8.78 (higher)	30.48 (smaller)

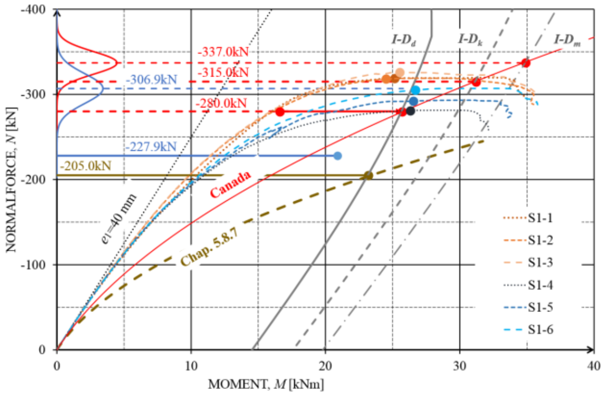


Figure 7: Safety format comparison procedure between the 'Canadian verification format' associated margin PDFstiff and the experimental margin PDF_{exp} of the tested columns (λ = 89, e_1 = 40 mm made of C45/55), see Table 6

4. SAFETY RESISTANCE FACTORS

4.1 Safety resistance factors of axial force capacity

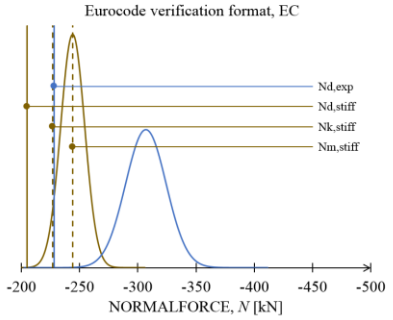
Figure 8(a) indicates the comparison of the axial force bearing capacity $N_{d,exp}$ (blue bars) obtained from the tests and the axial force bearing capacity $N_{d,stiff}$ (brown bars) obtained from the PDF_{exp} and PDF_{stiff} considerations of

Part I and sec. 3.1. It can be seen that the fractile value $N_{k,stiff}$ = 227.0 kN or design value of the axial force with $N_{d,stiff}$ = 205.00 kN are below the design values of the experiments $N_{d,exp}$ = 227.98 kN and are thus on the safe side. Nevertheless, the global safety factor of the code format determined using the safety format Estimation of COefficient of Variance of resistance (ECOV) with the code-derived LN (244.00, 10.33) is, with $\gamma_{\mathrm{R,stiff}}$ = 1.14, significantly smaller than the global safety factor derived from the experiments $\gamma_{\mathrm{R,exp}}$ = 1.21. Similar to the Eurocode verification format, the considerations were also carried out for the Chinese verification format, as seen in Figure 8(b). The comparison shows that the fractile value $N_{k,china}$ = 318.0 kN or design value of the axial force with $N_{d,china}$ = 282.30 kN are higher than the values of the experiments, e.g. $N_{d,exp}$ = 227.98 kN and are thus on the unsafe side. The ECOV-based global resistance safety factor concept applied to the Chinese verification format with N_{china} = LN (340.00, 13.37) results in a $\gamma_{\mathrm{R,china}}$ = 1.13. This standard-related factor is also significantly smaller than the global resistance safety factor of the experiments $\gamma_{\mathrm{R,exp}}$ = 1.21. In a final step, these considerations were also conducted for the American and Canadian verification formats, as seen in Figure 8(c) and (d). The fractile values $\mathrm{N_{k,U.S.}}$ = $N_{k,CA}$ = 315.0 kN or design values $\mathrm{N_{d,U.S.}}$ = $N_{d,CA}$ = 280.0 kN are higher than the values of the experiments, e.g. $N_{d,exp}$ = 227.98 kN and are thus on the unsafe side. The global resistance safety factor of both code formats determined using the ECOV method, based on LN (337.00, 13.37), is $\gamma_{\mathrm{R,US}}$ = 1.13, which is lower than the global safety factor derived from the experiments.

Table 7 provides a comprehensive overview of the determined PDF-specific values and the global resistance safety factor of the analyzed verification formats. As can be seen from these values, all values except for $N_{d,stiff}$ exceed the experimentally determined values.

In detail, the nominal stiffness format, accounting for shrinkage and creep and considering both axial force and moment, shows excellent results for single columns.

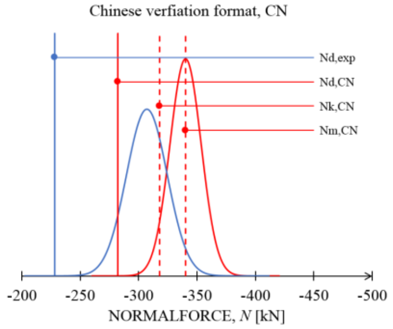
(a)



EC: $N_{d,stiff}$= 205.00 kN, $N_{k,stiff}$ = 227.00 kN

$\gamma_{R,stiff}$ = 1.14; LN (244.00, 10.33)

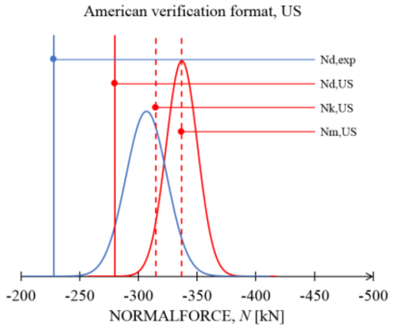
(b)



CN: $N_{d,CN}$ = 282.30 kN, $N_{k,CN}$ = 318.00 kN

$\gamma_{R,china}$ = 1.13; LN (340.00, 13.37)

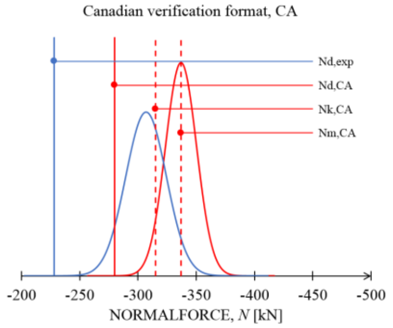
(c)



US: $N_{d,US}$ = 280.00 kN, $N_{k,US}$ = 315.00 kN

$\gamma_{R,US}$ = 1.13; LN (337.00, 13.37)

(d)



CA: $N_{d,CA}$ = 280.00 kN, $N_{k,CA}$ = 318.00 kN

$\gamma_{R,CA}$ = 1.15; LN (337.00, 11.55)

Figure 8: Descriptive values of the investigated verification formats and their global resistance factor concerning the values of the tested columns (λ = 89, e_1 = 40 mm made of C45/55), see Table 7.

The American and Canadian verification formats do not differ significantly from each other. However, both formats and the Chinese verification format applied to Eurocode I-D show significant differences from the experimental results. All three codes overestimate the axial force capacity and the global safety resistance factor.

Table 7: Descriptive statistical values of the investigated international verification formats and the global resistance factor of the tested columns (λ = 89, e_1 = 40 mm made of C45/55)..

	EC	CN	US	CA
γ_R	1.14	1.13	1.13	1.15
N_d	205 kN	282 kN	280 kN	280 kN
N_k	227 kN	318 kN	315 kN	318 kN
N_m	244 kN	340 kN	337 kN	337 kN
$> \gamma_{RExp}$	x	x	x	x
$< N_{dExp}$	●	x	x	x

Eurocode verification format, EC; Chinese verfiation format, CN; American verification format, US; Canadian verification format, CA; a) > $\gamma_{R\,Exp\,(eq.\,4\text{-}1)}$ = 1.21 , b) <$N_{d,Exp\,(eq.\,4\text{-}3)}$ = 227.90 kN

4.2 Safety resistance factors of moment capacity

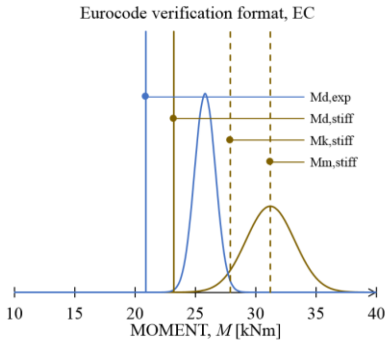
For the analysis of the global safety resistance factors of the moment load capacity, the procedural steps of sec. 3.1 were carried out similarly for the moments to determine the $\mathrm{PDF}_{\mathrm{country}}$ in compliance with the Eurocode I-D's, see Figure 2. Comparing the moment bearing capacity $M_{d,exp}$ (blue bars) obtained from the tests and the axial force bearing capacity $M_{d,stiff}$ (brown bars) obtained from the $\mathrm{PDF}_{\mathrm{exp}}$ and $\mathrm{PDF}_{\mathrm{stiff}}$ considerations of Part I and sec. 3.1 is shown in Figure 9.

It can be seen from Figure 9(a) that the fractile value $M_{k,stiff}$ = 29.80 kNm or design value of the axial force with $M_{d,stiff}$ = 24.28 kNm are above the design values of the experiments $M_{d,exp}$ = 20.89 kNm and are thus on the unsafe side.

Nevertheless, the global safety factor of the code format determined using the safety format ECOV with the code-derived LN (32.8, 1.34) is, with $\gamma_{R,\mathrm{stiff}}$ = 1.13, significantly smaller than the global safety factor derived from the experiments $\gamma_{R,\mathrm{exp}}$ = 1.21.

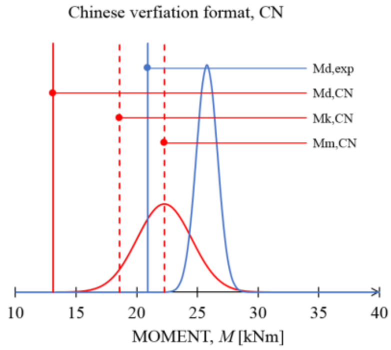
The results of the analyses for the Chinese, American and Canadian verification formats are documented in Figure 9(b) to (d).

(a)



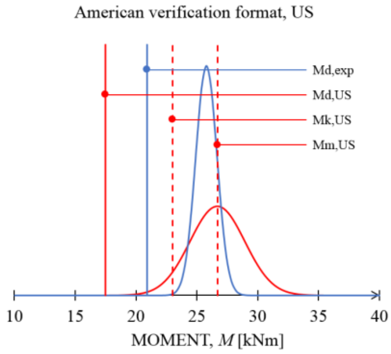
EC: $M_{d,stiff}$= 24.30 *kNm*, $M_{k,stiff}$ = 30.70 *kNm*
γ_R = 1.13; LN (32.80, 1.34)

(b)



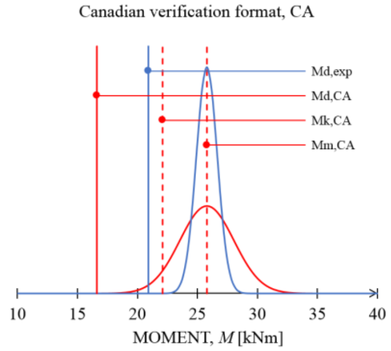
CN: $M_{d,CN}$= 13.10 *kNm*, $M_{k,CN}$ = 19.50 *kNm*
γ_R = 1.34; LN (22.80, 2.13)

(c)



US: $M_{d,US}$= 17.50 *kNm*, $M_{k,US}$ = 24.30 *kNm*
γ_R = 1.28; LN (27.7, 2.19)

(d)



CA: $M_{d,CA}$= 16.60 *kNm*, $M_{k,CA}$ = 23.40 *kNm*
γ_R = 1.29; LN (26.8, 2.19)

Figure 9: Descriptive values of the investigated verification formats and its global resistance factor to the values of the tested columns (λ = 89, e_1 = 40 mm made of C45/55), see Table 8.

These results are also summarized in Table 8, which shows a comprehensive overview of the determined PDF-specific values and the global resistance safety factor of the analyzed verification formats. As can be seen from these values, all values except for $M_{d,stiff}$ are below the experimentally determined values. All investigated verification formats applied to Eurocode I-D except the Eurocode format show significant differences to the experimental results $M_{d,exp}$ = 20.89 kNm. All three investigated codes underestimate the moment capacity and overestimate the global safety resistance factor in the moment capacity.

Table 8: Overview of the statistical parameters and the global safety factors of the bending moment values of the analyzed code design methods and the experimentally obtained bending moments of the columns made of concrete grade C45/55

	EC	CN	US	CA
γ_R	1.13	1.34	1.28	1.29
M_d	24.3 kNm	13.1 kNm	17.5 kNm	16.6 kNm
M_k	29.8 kNm	19.5 kNm	24.3 kNm	23.4 kNm
M_m	32.8 kNm	22.8 kNm	27.7 kNm	26.8 kNm
$>M_{d,Exp}$	●	x	x	x
$>\gamma_{RExp}$	x	●	●	●

Eurocode verification format, EC; Chinese verfiation format, CN; American verification format, US; Canadian verification format, CA; a) $>M_{d,\,Exp\,(eq.\,4\text{-}1)} = 20.89$kNm, b) $> \gamma_{R\,Exp\,(eq.\,4\text{-}1)} = 1.21$

4 CONCLUSIONS

The objective of these contribution was to conduct an international comparison of column stability verification and its numerical and quality control formats used in standardization documents. Specifically, the formats used in Asian, American, and European countries were verified concerning results obtained from a column testing campaign on specific column layouts. The documents provided by the respective country representatives show that most of the standards are based on the four concepts implemented in the Eurocode:

(a) The 'nominal curvature' method, where second-order moments are determined from an estimation of the column curvature. These second-order moments are added to the first-order moments to provide the total column design moment.

(b) The 'moment magnification' method, where the design moments are obtained by factoring the first-order moments.

(c) A second-order analysis based on nominal stiffness values of the beams and columns that, again, requires computer modeling and iterative analysis.

(d) A general method based on nonlinear analysis of the structure and allowing for second-order effects that necessitate the use of computer analysis.

These methods are, in particular, permitted in a more or less modified form in the 'Chinese verification format', the 'American verification format', and the 'Canadian verification format'. However, they are not permitted in the 'Japanese verification format'. Although several studies on the behavior of slender reinforced concrete (RC) columns have been carried out in countries without strong earthquake risks, research on civil engineering structures (e.g., bridges and highway bridges) in Japan has focused only on the flexural performance of short columns. It should be noted that since all highway bridges in Japan are designed considering the high intensity of seismic effects, the typical shear span ratio of RC columns in Japan is much smaller than that of RC columns located in non-earthquake-prone regions. This is why the impact of the slenderness ratio on the flexural strength of RC columns does not need to be considered in Japan.The investigations in this paper also show significant differences in the safety levels of the EN 1992-1-1 verification formats. In particular, according to EN 1992-1-1 Chapter 5.8.6 (3), the permitted nonlinear numerical analysis method results in a significant undercut of the reference global safety factor.

These investigations have been based on the Round-Robin experimental tested and modelled columns [2].

The detailed safety format investigations also showed that the I-D diagrams of the participating countries differ significantly from each other and that the comparison of the safety formats of the country-specific *N-M* gradients has to be related to a reference I-D’s, e.g. the Eurocode I-D’s.

As seen from the performed studies, all values except for $N_{d,stiff}$ exceed the experimentally determined values. The American and Canadian verification formats do not differ significantly from each other. However, both formats and the Chinese verification format applied to Eurocode I-D show significant differences from the experimental results. All three codes overestimate the axial force capacity and the global safety resistance factor. In addition, all investigated verification formats applied to Eurocode I-D except the Eurocode format show significant differences to the experimental results $M_{d,exp}$. All three investigated codes underestimate the moment capacity and overestimate the global safety resistance factor in the moment capacity. This study's results show the need to review and extend the Eurocode safety concept, as seen from the significant variations in the global safety factor. As well as the need to identify the reasons for the small moment capacities of the international codes concerning the Eurocode results. Furthermore, the large deviations in the I-D’s of the considered columns would have to be clarified.

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