TENSION-STIFFENING BEHAVIOUR OF REINFORCED CONCRETE TIES OF VARIOUS STRENGTH CLASSES

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ABSTRACT

A new law of tension-stiffening for reinforced concrete (RC) ties is proposed in the present study. It is based on the test data of 11 experimental programs of RC elements of various strength classes reported in the literature. The experimental programs covered a wide range of characteristics of mechanical and geometrical parameters of specimens such as compressive strength of concrete, reinforcement ratio and diameter of reinforcement bars. By eliminating the effect of shrinkage from the test load-strain diagrams of the ties, a simple model with no dependence on reinforcement ratio could be derived. The proposed tension-stiffening law is compared with the formulation in Eurocode 2. Statistical analysis of strain predictions of RC ties based on Eurocode 2 was conducted. It is found that the Eurocode 2 significantly underestimated strains in the RC ties with the errors reaching 50% for the lightly reinforced members. Nevertheless, when shrinkage effect was accounted for in the test load-strain diagrams, the predictive capability of the Eurocode 2 formulation could be significantly improved.

KEYWORDS

Reinforced concrete ties, tension-stiffening, shrinkage effect.

INTRODUCTION

The stiffness of a reinforced concrete (RC) member loaded in axial tension can be considered as the superposition of the stiffness of reinforcement and the stiffness of plain concrete. When the RC member is cracked, the stiffness of intact concrete is reduced to that of cracked concrete, this is referred to as tension softening. In addition, there is a stiffness component due to bond between concrete and reinforcement, this is referred to as the tension-stiffening component. Tension softening is a property of plain concrete and can be simulated by fracture mechanics models. Tension-stiffening is a property of cracked concrete under tensile stress in the presence of bar reinforcement. Due to the bond with reinforcement, the intact cracked concrete between cracks carries a certain amount of tensile force normal to the cracked plane and contributes to the overall stiffness of the structure.

Tension-stiffening has been vastly researched in a variety of approaches (Torres *et al*. 2004; Ng *et al*. 2010; Lam *et al*. 2010; Gilbert and Ranzi 2011). In the present analysis, a simplified approach based on smeared cracks is followed in which the stress in the concrete is taken as the combined stress due to both tension-stiffening and tension softening, collectively called the tension-stiffening. Based on this approach, a number of stress-strain constitutive relationships for cracked tensile concrete have been proposed, as exemplified by the studies of Prakhya and Morley (1990) and Christiansen and Nielsen (2001). However, most of the studies in the literature did not take into account the shrinkage effect. The influence of shrinkage on short-term and long-term strains and tension-stiffening in reinforced concrete members has been investigated by Bischoff (2001), Fields and Bischoff (2004), Kaklauskas *et al*.(2009), Kaklauskas and Gribniak (2011). A technique to exclude the shrinkage effect from the load-strain relationships of RC ties was proposed by Bischoff (2001). Based on this technique, he developed a shrinkage-free tension-stiffening law. However, limited amount of experimental data were used in deriving the constitutive relationship, and this might limit the applicability of the tension-stiffening law.

The present study proposes a new law of tension-stiffening for RC ties. Its derivation is based on the test data of 11 experimental programs of RC elements of various strength classes (Scott and Gill 1987; Stroband 1991; Farra and Jaccoud 1993; Lorrain *et al*. 1998; Noghabai 2000; Choi and Maekawa 2003; Wu and Gilbert 2008;

Yuguang *et al*. 2009; Danielius 2014; Gudonis *et al*. 2014; Kesminas and Tamulenas 2014). These experimental programs covered a wide range of characteristics of mechanical and geometrical parameters of specimens including the compressive strength of concrete, reinforcement ratio, and diameter of reinforcement bars. A distinctive feature of the proposed constitutive law is the expression of tension-stiffening stresses in terms of the compressive strength of concrete. This is desirable from practical viewpoint since the uncertainty and empiricism associated with the equation determining tensile strength of the concrete could be avoided. Furthermore, the study also reports the statistical analysis results of strain predictions of the RC ties using the Eurocode 2 formulation.

DESCRIPTION OF COLLECTED EXPERIMENTAL DATA

The present analysis is based on the data collected from 11 experimental programs, listed in Table 1, which involved 136 RC elements (3,498 measurements) of different strength classes. All specimens were subjected to short-term axial tension. All experimental programs involved prismatic specimens with square sections reinforced by a single bar. The specimens were tested either by controlling the deformations, as adopted in programs No. 1-8 and 11, or alternatively, controlling the applied tensile force, as adopted in programs No. 9 and 10.

The main characteristics of the specimens are given in Table 1, where the first four columns refer to the test program number, the literature source of the program, the numbers of the tested elements, and the number of measurements in this program, respectively. The experimental programs in Table 1 are listed in descending order of the number of the measurements, n. Further parameters in Table 1 are: the height (h) and width (b) of the section; the concrete cover (c); the length of the specimen (L); the diameter of the reinforcement bars (D); the total area the reinforcement (A_s); the reinforcement ratio (p); the compressive strength of the ∅150×300 mm concrete cylinder (f_{cm}), and the shrinkage strain (ε_{cs}) measured at the age of testing. When the values of the parameters varied within a range, the range of values rather than individual values are stated in the table.

Table 1. Main characteristics of the test specimens used for the constitutive modelling

No.	*Reference*	*No. of elements*	*n*	h	b	c	L	D	A_s	p	f_{cm}	ε_{cs}
				mm					mm²	%	MPa	μm/m
1	Farra & Jaccoud (1993)	1-100	2291	100	100	40-45	1150	10-20	79-314	0.8-3.2	35.4-88.1	–
2	Danielius (2014)	101-107	252	100	100	43-45	1000	10-14	79-154	0.8-1.6	53.1	82-121
3	Gudonis *et al*. (2014)	108-113	165	100-103	100-112	44-46	1500	12	113	1.0-1.1	33.6	–
4	Kesminas & Tamulenas (2014)	114-119	158	80	80	34	1000	12	113	1.8	45.3	389-459
5	Wu & Gilbert (2008)	120-123	156	100	100	42-44	1100	12-16	113-201	1.1-2.1	21.6-24.7	28-249
6	Noghabai (2000)	124-126	117	80-112	80-112	32-48	960	16	201	1.6-3.2	45.6-92.4	–
7	Stroband (1991)	127-129	108	100	100	42-44	935	12-16	113-201	1.1-2.1	18.4-49.6	–
8	Choi & Maekawa (2003)	130-132	106	100	100	42	1470	16	201	2.1	35.1-40.5	–
9	Lorrain *et al*. (1998)	133-134	67	100	100	44	2000	12	113	1.1	42.0-101.0	–
10	Scott & Gill (1987)	135	39	103	101	46	1500	12	86	0.8	36.0	–
11	Yuguang *et al*. (2009)	136	39	50	50	20	700	10	79	3.2	98.8	–

Note: The shrinkage deformations ε_{cs} are negative; the symbol "–" indicates that the experimental shrinkage strain was not provided and is thus assessed using the Eurocode 2 formulation.

MODELLING OF TENSION-STIFFENING

The present study aims at developing a tension-stiffening model that combines the objectives of accuracy and simplicity. The original tension-stiffening relationships in terms of mean stress-mean strain diagrams were obtained from the load-mean strain relationships. The material characteristics of concrete such as the tensile strength, f_{ct}, and the modulus of elasticity, E_c, were assessed in accordance with the Eurocode 2 using the respective values of the compressive strength as stated in Table 1.

Derivation of Tension-Stiffening Law

A statistical data set was composed using the tensile stress-strain relationships obtained for each of the ties. It should be noted that the ties had different geometric and material characteristics (Table 1), resulting in different cracking resistance and ultimate strength. Moreover, the objectives of the experimental programs were different and different loading steps with different measurement intervals were considered in these programs. To assure an even contribution of each experimental specimen, the data set was composed by applying an interpolation procedure developed by the authors (Gribniak *et al*. 2013a, 2013b). To have equal representation of different loading levels, the data set included the test points corresponding to certain levels of normalized strains ($\varepsilon_m/\varepsilon_{cr}$ = 1.0, 1.5, 2.0, 2.5,…). Here ε_m and $\varepsilon_{cr} = f_{ct}/E_c$ are the mean strain and the cracking strain of concrete, respectively. The tension-stiffening diagrams were terminated at the yield load.

Various tension-stiffening models suggest that tension-stiffening stress-strain relationship might be dependent on a number of parameters, the most important of which are the tensile strength of concrete, reinforcement ratio and modular ratio (Torres *et al*. 2004; Gribniak *et al*. 2015). As the starting point, Figure 1 plots the target points of normalized stress (σ_{ct}/f_{ct}) and relative strain ($\varepsilon_m/\varepsilon_{cr}$) generated from the experimental programs.

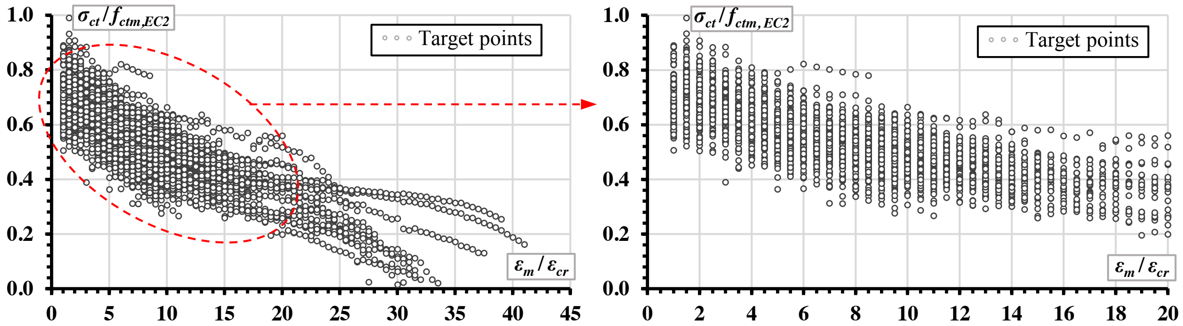

Figure 1. Normalized target tension-stiffening stresses versus the relative strain

The constitutive modeling was devised by curve fitting with the goal to minimise the error of the target tension-stiffening stresses σ_{ct} at different relative strain levels. An emphasis was placed on the strain interval of $\varepsilon_m/\varepsilon_{cr} < 20$ which affects to a large degree the load-deformation response. From a number of possible fitting curves considered, as a compromise between accuracy and simplicity, the following form for the descending part of the σ_{ct}-ε_m relationship as given in Eq. (1) is proposed and is plotted in Figure 2:

$$\sigma_{ct} = 3 - 12.5/f_{cm}{}^{0.5} + 1.76 \cdot e^{-\varepsilon_m} \tag{1}$$

In the above, σ_{ct} is the tensile (tension-stiffening) stress, f_{cm} is the mean compressive strength, and ε_m is the mean tensile strain. A notable feature of the proposed constitutive law is that it is related to the compressive strength of concrete. Unlike most tension-stiffening laws that are expressed in terms of the tensile strength of concrete, the proposed model circumvents the empiricism associated with the equations determining tensile strength of the concrete. Per Eq. (1), the stress-strain relationship is plotted in Figure 2 with juxtaposition of the scattered target points. It is noted that the test data and the proposed model agree well with each other, in particular over the strain interval of $\varepsilon_m/\varepsilon_{cr} < 20$, as shown in the right hand side of Figure 2.

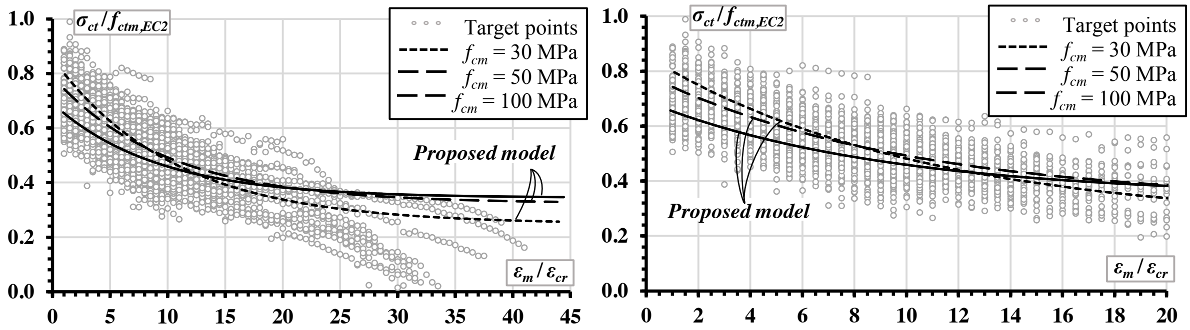

Figure 2. Proposed stress-strain relationship for RC members in tension

As can be seen from Figure 2, the maximum stresses do not reach the tensile strength of concrete f_{ct} as suggested in Eurocode 2. This is in line with previous research findings (Gupta and Maestrini 1990). For lower concrete grades, the maximum normalized stresses tend to be slightly larger, i.e. closer to unity. This would be attributed to the fact that for a given reinforcement area, a lower concrete grade would lead to greater contribution from the reinforcing steel to the overall resistance of the RC element.

Elimination of Shrinkage Effect

Tension-stiffening is significantly affected by the shrinkage of concrete occurring prior to loading. In general, the shrinkage behaviour is dependent on the properties of concrete (including the mix proportioning and the type of ingredients), environmental factors (including temperature and humidity), and geometrical characteristics of the RC member (including the effective thickness and exposed perimeter). The above factors have been accounted for in the formulas for estimating shrinkage in Eurocode 2. The elimination of shrinkage from the load-deformation response of RC elements is of key importance in deriving an universally applicable tension-stiffening law. Herein, the exclusion of shrinkage effect is principally in accordance with the shrinkage elimination techniques reported in Bischoff (2001) and Kaklauskas *et al.* (2009). Basically, the shrinkage is modelled by a fictitious force N_{sh} causing the equivalent deformation of the member taking into account the effect of creep. The fictitious force is determined by considering a plain concrete member having the sectional area A_c and deformation modulus E_{ca} (through which the creep deformation is accounted), and subjected to compression so as to impose the axial strain ε_{sh}, therefore:

$$N_{sh} = \varepsilon_{sh} E_{ca} A_c \tag{2}$$

where E_{ca} is related to the modulus of elasticity of concrete E_c by the creep factor φ and the ageing coefficient χ:

$$E_{ca} = E_c/(1 + \varphi\chi) \tag{3}$$

Regarding the shrunk RC member, the shrinkage-induced internal forces acting in the steel and concrete would be equal and opposite, and the deformation of member can be obtained based on the principles of equilibrium and compatibility. The stress of concrete can be deduced as shown in Eq. (4) and the strain state of the member is represented by the effective shrinkage strain $\bar{\varepsilon}_{sh}$ in Eq. (5) (Kaklauskas *et al.* 2009):

$$\sigma_{c,sh} = -\varepsilon_{sh} E_s \rho / [1 + (E_s/E_{ca})\rho] \tag{4}$$

$$\bar{\varepsilon}_{sh} = \varepsilon_{sh} \frac{1+(E_s/E_c)\rho}{1+(E_s/E_{ca})\rho} \tag{5}$$

By the principle of superposition, the experimental load-strain curves of the RC ties were adjusted to discount for the shrinkage. The superposition was applied to every discrete point along the stress-strain response to yield the target points for deriving the tension stiffening law herein. The target points with eliminated shrinkage effect are shown in Figures 1 and 2.

Theoretically, by virtue of Eqs (4) and (5), the tension-stiffening stress will be dependent on the reinforcement ratio. Nevertheless, the proposed law in Eq. (1) could provide acceptable results without significant error. Hence, the authors are of the view to simplify the model to omit the dependence on ρ.

Comparison with Eurocode 2

Stress-strain relationships of RC ties with different concrete strengths can be derived based on the proposed tension-stiffening law. The tension-stiffening stress curves corresponding to concrete grades C25, C35, C45 and C55 are plotted in Figure 3 for comparison with the Eurocode 2. The calculation procedures of tension-stiffening relationships for the RC ties according to Eurocode 2 are as follows. The governing equation relating the tensile strain and tensile stress is expressed in terms of the deformation parameter α as:

$$\varepsilon_m/\varepsilon_{cr} = \alpha/\left(f_{ctm,EC2}/E_{cm}\right) \tag{6}$$

where ε_{cr} is the cracking strain, $f_{ctm,EC2}$ is the mean tensile strength, and E_{cm} is the mean elastic modulus of concrete.

The deformation parameter α varies between the value at uncracked condition α_{I} and the value at fully cracked condition α_{II}, and the variation of α is described by the distribution coefficient ζ.

$$\alpha = \zeta\alpha_{\mathrm{II}} + (1 - \zeta)\alpha_{\mathrm{I}} \tag{7}$$

The variables in Eq. (7) are given mathematically by:

$$\zeta = 1 - \beta(P_{cr}/P)^2 \tag{8}$$

$$\alpha_{\mathrm{I}} = P/(A_cE_c + A_sE_s) \tag{9}$$

$$\alpha_{\mathrm{II}} = P/(A_sE_s) \tag{10}$$

In Eqs (8) to (10), β is a coefficient taking account of the influence of duration of loading or repeated loading and it has the value of 1.0 for short-term loading and 0.5 for sustained loading or repeated loading, P is the axial load, P_{cr} is the axial load at cracking, A_c is the cross sectional area of concrete, and E_s is the modulus of elasticity of reinforcing steel.

From the above, the equation of stress-strain relationship in Eurocode 2 can be expressed as:

$$\sigma_{ct}/f_{ctm,EC2} = \left(\frac{P-\alpha E_sA_s}{A_c}\right)/f_{ctm,EC2} \tag{11}$$

By using Eq. (11), stress-strain relationships of RC ties with reinforcement ratios varied amongst 0.2%, 0.5%, 1.0% and 2.0% were derived and they are included in Figure 3. As can be seen from the figure, the tension-stiffening relationships obtained from Eurocode 2 show a strong dependence on the reinforcement ratio, while the role of concrete grade is less influential on the normalized stress. The proposed law best fits the Eurocode 2 relationship of RC ties with reinforcement ratio of 2.0%.

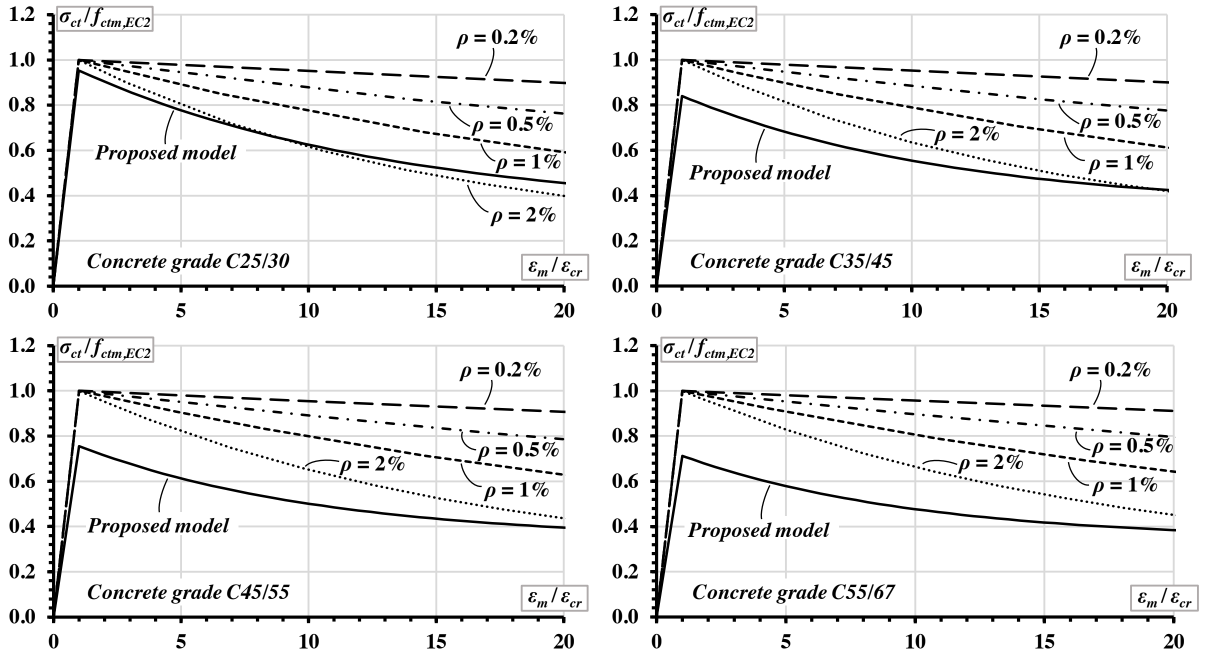

Figure 3. The proposed model compared to the tension-stiffening relationships obtained from Eurocode 2

STATISTICAL ANALYSIS OF STRAIN PREDICTIONS

The tensile strains of experimental specimens were compared with those predicted based on Eurocode 2. To conduct the analysis, ten levels of load intensity P' taken in relative terms between the cracking and ultimate tensile forces are established:

$$P' = (P - P_{cr})/(P_{ult} - P_{cr})\,;\; P' = \{0.1; 0.2; \ldots; 0.9; 1\} \tag{12}$$

where P_{ult} denotes the theoretical ultimate tensile force assuming the yielding strength of reinforcement $f_y = 500$ MPa. The cracking load P_{cr} is given by:

$$P_{cr} = f_{ct}(A_c + \eta A_s). \tag{13}$$

In the above, f_{ct} is the tensile strength of concrete, and η is the modular ratio and is equal to E_s/E_c. Thus, when P' is equal to 0, it corresponds to cracking; and when P' is equal to 1, it corresponds to the theoretical failure of the RC element.

The accuracy of predictions was evaluated by means of the relative error $\Delta_{i,k}$, which is calculated at each level of P' for each of the 136 experimental members:

$$\Delta_{i,k} = \varepsilon_{calc} / \varepsilon_{obs}, \quad i = 1; 2; 3; \ldots; 10, \quad k = 136; \tag{14}$$

in which ε_{calc} and ε_{obs} are the strains interpolated at the level P' from calculation and from original test data, respectively. It should be noted that not all specimens contained eleven output points as their testing was terminated before the stress of reinforcement reached 500 MPa. The transformation resulted in 654 output points covering the post-cracking stage (compare to 3498 measured points).

It was intended at each normalized load level to define intervals of reinforcement ratio with normal probability distribution of relative error Δ. Such stratification aims at improving the reliability of strain prediction method. Analysis of the data has resulted in two such intervals:

$$1{:}\, p < 1.6\%; \quad 2{:}\, p \geq 1.6\%. \tag{15}$$

After applying the stratification based on the above intervals, the mean m_Δ and standard deviation s_Δ were calculated at each normalized load level. The statistics for each of the strain calculation method are presented in Table 2.

Table 2. Statistics (mean and standard deviation) for analytical strain calculations

P'	***n***	***Eurocode 2***		***n***	***Eurocode 2, eliminated shrinkage***		***n***	***Eurocode 2***		***n***	***Eurocode 2, eliminated shrinkage***	
	Pts.	m_Δ	s_Δ	***Pts.***	m_Δ	s_Δ	***Pts.***	m_Δ	s_Δ	***Pts.***	m_Δ	s_Δ
			$p < 1.6\%$						***$p \geq 1.6\%$***			
0	61	0.124	0.128	64	0.228	0.178	54	0.189	0.115	54	0.493	0.226
0.1	56	0.317	0.199	64	0.455	0.273	49	0.540	0.133	54	0.839	0.178
0.2	51	0.436	0.178	64	0.546	0.227	45	0.694	0.116	54	0.931	0.140
0.3	38	0.517	0.213	64	0.614	0.224	12	0.780	0.147	48	0.979	0.097
0.4	28	0.561	0.239	58	0.671	0.241	9	0.807	0.140	19	1.016	0.103
0.5	16	0.574	0.312	45	0.682	0.266	9	0.840	0.115	9	0.997	0.092
0.6	13	0.572	0.340	36	0.687	0.257	9	0.864	0.092	9	1.002	0.075
0.7	12	0.571	0.349	27	0.679	0.259	9	0.882	0.081	9	1.006	0.060
0.8	11	0.545	0.334	17	0.643	0.286	9	0.896	0.068	9	1.012	0.048
0.9	10	0.556	0.358	15	0.624	0.272	9	0.909	0.059	9	1.012	0.045
1	10	0.570	0.365	11	0.689	0.277	8	0.910	0.054	9	1.015	0.038

Graphical representation of the statistical analysis results is given in Figure 4, where the 95% confidence intervals of expectation μ_Δ for the grouped data are shown. The width of confidence intervals characterizes the variations of the relative error of predictions:

$$\mu_\Delta \in \left[m_\Delta - t_{1-\alpha/2}(n-1) \times \frac{s_\Delta}{\sqrt{n}};\ m_\Delta + t_{1-\alpha/2}(n-1) \times \frac{s_\Delta}{\sqrt{n}} \right] \tag{16}$$

where $t_{1-\alpha/2}(n-1)$ is the t-statistics (i.e. following Student's t-distribution) having $(n–1)$ degrees of freedom and significance level $\alpha/2$, and $(1–\alpha)$ is confidence coefficient.

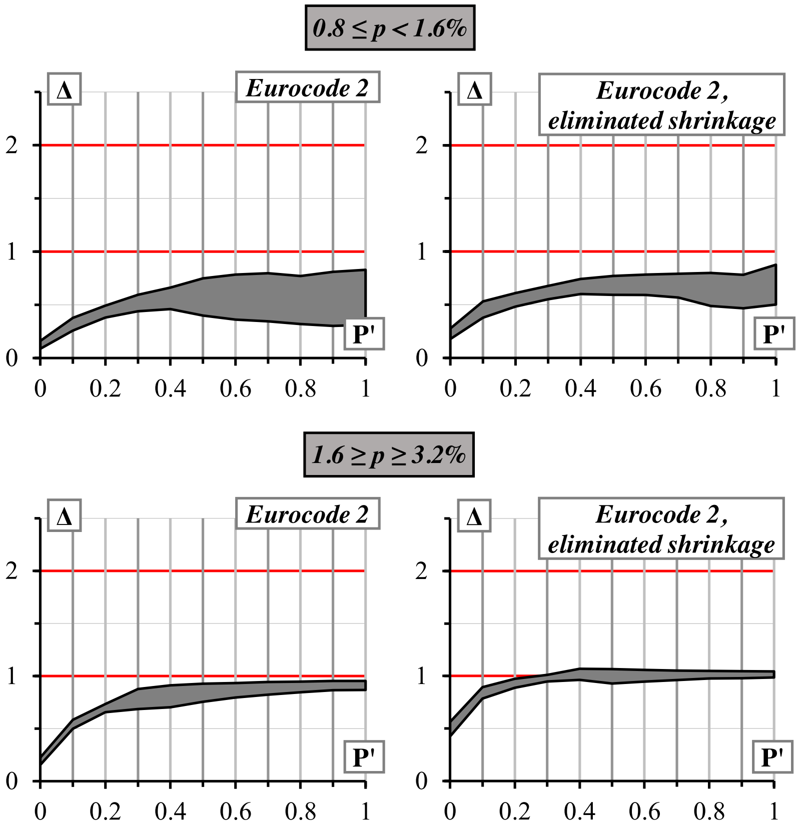

Figure 4. 95% confidence intervals ($0.8 \leq p \leq 3.2\%$)

From Figure 4, it is evident that the accuracy of strain predictions by Eurocode 2 varied significantly with the load intensity and amount of reinforcement. Generally, Eurocode 2 notably underestimated strains, particularly in the lightly reinforced members (p < 1.6%), for which the predictions on average were only 50% of the experimental values. Higher accuracy was achieved for the members with larger amounts of reinforcement with the predictions on average reaching 80% of the test results. However, at earlier loading stages, the accuracy of strain predictions was worse.

To reveal the shrinkage influence on the Eurocode 2 predictions, separate analysis was performed using the experimental load-strain relationships with elimination of the shrinkage effect, which is assessed in accordance with the provisions in Eurocode 2. In this case, the predictions for the members with higher reinforcement ratio became more accurate even at earlier loading stages, whereas the error for the lightly reinforced ties was reduced remarkably to about 20%. Elimination of the shrinkage effect also led to a much smaller scatter of the predictions with maximum standard deviation decreased by 30% among the lightly reinforced members (p < 1.6%) (refer to Table 2). Hence, by accounting for the shrinkage effect, the accuracy of strain prediction could be significantly improved. Desirable results in terms of consistency and variation are obtained. These findings of RC ties echo with the research findings by Gribniak *et al.* (2013c), who reported significant improvement in deflection prediction of RC beams by accounting for the shrinkage effect, as compared to the provisions in Eurocode 2.

CONCLUSIONS

A new law of tension-stiffening with exclusion of shrinkage effect has been developed. It is based on the test data of 11 experimental programs encompassing 136 reinforced concrete (RC) ties of various strength classes covering a wide range of characteristics of mechanical and geometrical parameters including compressive strength of concrete, reinforcement ratio and diameter of reinforcement bars. A distinctive feature of the proposed constitutive law is the expression of tension-stiffening stresses in terms of the compressive strength of concrete, thereby avoiding the uncertainty and empiricism of the equations determining the tensile strength of concrete. Based on the proposed law, the stress-strain relationships of RC ties of concrete grades C25, C35, C45 and C55 have been derived and compared with the Eurocode 2 formulations. Among the different reinforcement ratios of 0.5%, 1.0%, 1.5% and 2.0% considered for the Eurocode 2 relationship, it has been found that the proposed law best fits the Eurocode 2 curves of reinforcement ratio equal to 2.0%.

Statistical analysis of results from experimental programs and strain predictions of the RC ties using Eurocode 2 was performed. The analysis has evaluated the adequacy of the application of Eurocode 2. The following main conclusions can be drawn:

1. Accuracy of strain predictions by the Eurocode 2 varied significantly with load intensity and amount of reinforcement.
2. The Eurocode 2 significantly underestimated strains of the RC ties. For the lightly reinforced members ($p < 1.6\%$), the predictions on average was approximately 50% of the experimental values. Higher accuracy was achieved for the members with larger amounts of reinforcement with the predictions on average reaching 80% of the test results. Generally, at earlier loading stages, the accuracy of strain predictions was worse.
3. The Eurocode 2 technique appears to be a much more accurate tool for predicting strains in the RC ties, if the prediction results are compared to the test results with the elimination of shrinkage effect. In the case of heavily reinforced ties, the predictions become more accurate even at earlier loading stages, whereas the error for the lightly reinforced ties is reduced to about 20%. Elimination of the shrinkage effect also led to much smaller scatter of the predictions.

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