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A METHOD FOR DETERMINATION OF STRESS-STRAIN RELATIONS FOR CONCRETE FROM EXPERIMENTAL DATA OF RC BENDING MEMBERS

G. Kaklauskas

1. Introduction

Traditional methods of analysis and design of reinforced concrete structures are based on equilibrium conditions and empirical formulae. Empirical techniques are developed on a basis of a great number of experiments and often lead to cumbersome expressions having no physical meaning. Design codes based on traditional methods assure safe design, but do not reveal the actual behaviour of cracked reinforced concrete structures. Due to complexity of the behaviour mainly caused by cracking, shrinkage and creep effects, reinforced concrete structures are often considered as an independent branch of structural science. However, it is strongly believed that further development of the analysis methods should be based on modification of the universal methods of strength of materials and structural mechanics. Thus, for bending members the layered approach most naturally reflects the behaviour of such members made both from a linear and a nonlinear material. By this approach for assumed material relationships, a stress-strain state can be determined for any load stage. Such analysis of experimental reinforced concrete flexural members subjected to short-term loading have shown that an adequate modelling of tension stiffening effect is mostly responsible for accuracy of the computed deflections. Sometimes tension stiffening is confused with tension softening. The latter is a property of plain concrete and tension stiffening is a property of reinforced concrete. Due to bond with reinforcement, the cracked concrete between cracks carries a certain amount of tensile force normal to the cracked plane. The concrete adheres to the reinforced bars and contributes to overall stiffness of the structure.

Several approaches based on experimental results for reinforced concrete are proposed in the literature [1-6]. Tension stiffening effect is often modelled by the descending branch of a stress-strain relationship for tensile concrete shown in Fig 1. The relationship is characterized by parameters α_1 and α_2. Values of α_2 proposed by different authors [1,3,5] range from 5 to 25. Moment-curvature diagrams computed for an actual experimental beam [7] assuming α_2 equal to 5 and 25 are shown in Fig 2. A cross-section and material properties of the beam are presented in Fig 2(a). A stress-strain relationship for compressive concrete was assumed according to eq (22). Two reinforcement ratio levels were assumed: the actual one (p = 0.94%) and the twice decreased (p = 0.47%). As it seen from Fig 2(b), change in parameter α_2 significantly affected the moment-curvature diagrams. The effect is particularly clear for the section with the lower reinforcement ratio at the initial cracking stages.

Experimental investigation of tensile [8] and flexural [9,10] members have shown that the tension stiffening effect is mostly dependent on the diameter of reinforcement bars, reinforcement ratio, concrete strength in tension, and the distribution of reinforcement. An attempt was made by Prakhya and Morley [11] to include into the stress-strain curve several parameters affecting the tension stiffening. On a basis of simplified assumptions, using the test data [8-10], they modified an equation of the stress-strain curve proposed by Carreira and Chu [6].

Most of the publications, discussing tension stiffening effect and the shape of the stress-strain relationship of concrete in tension, disregard shrinkage effects.

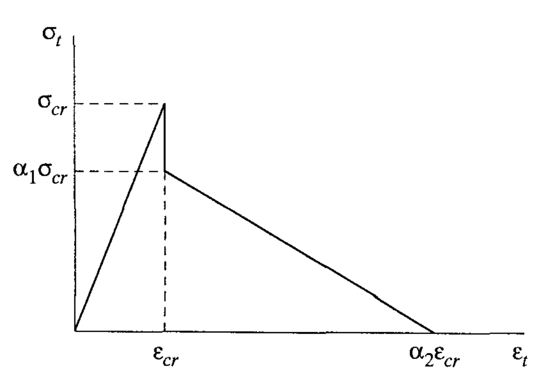
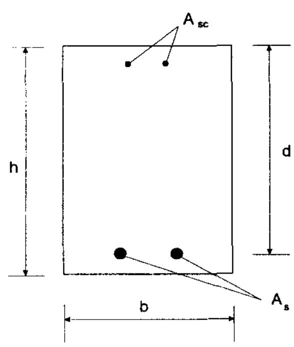


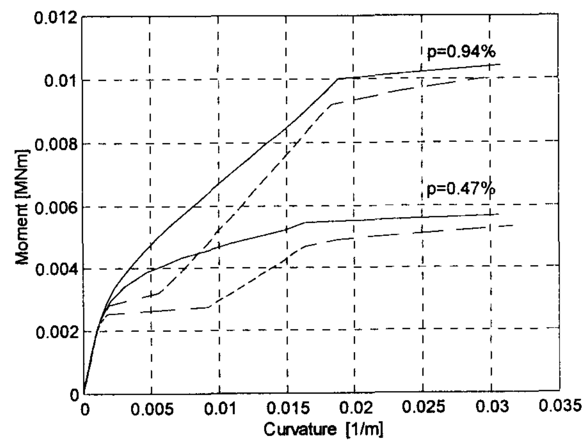
Fig 1. Average stress-strain relation for concrete in tension

a



$h = 0.18$ m; $b = 0.10$ m;
$d = 0.16$ m;
$A_s = 1.51 \cdot 10^{-4}$ m²;
$A_{sc} = 0.51 \cdot 10^{-4}$ m²;
$E_c = 3.95 \cdot 10^{-4}$ MPa;
$f_c' = 41.25$ MPa;
$\varepsilon_0 = 0.0021$;
$f_{cr} = 3.0$ MPa;
$E_s = 1.97 \times 10^5$ MPa;
$f_y = 420$ MPa;
$p = 0.94\%$.

b



———— $\alpha_2 = 25$; — — — $\alpha_2 = 5$

Fig 2. Influence of stress-strain relation for tensile concrete on curvature of reinforced concrete members

Even at early ages of concrete, shrinkage may lead to significant tensile stresses in concrete, particularly for members with higher reinforcement ratios. Unfortunately, determination of stresses in reinforced concrete structures caused by shrinkage is hampered by uncertainty of prediction of the free concrete shrinkage strain which estimates obtained from different methods vary widely.

In usual structural analysis problems, strength and strains (curvature) have to be defined when material properties are given. Unfortunately, assumed material stress-strain relationships often are too simplified, do not reflect a complex multi-factor nature of the material and therefore are inaccurate. Such an example is a material stress-strain relationship for concrete in tension shown in Fig 1. Due to bond with steel, tensile concrete in cracked reinforced concrete structures has properties different from those obtained in simple material tests. It must be noted that concrete stress-strain curves obtained from tension tests of reinforced concrete members do not necessarily assure accurate results for calculation of bending structures. Therefore, quite naturally a researcher is challenged by the idea to solve a problem of bending analysis in an opposite way: to derive concrete material stress-strain relations for given experimental moment-strain (curvature) diagrams. Subsequently, on a basis of such relations a new stress-strain calculation model could be developed.

A new method has been developed for determining concrete stress-strain relations from experimental data of flexural reinforced concrete structures. In this paper, the formulation of the method is presented.

2. Assumptions

The present work is based on the following assumptions of behaviour of flexural reinforced concrete members:

(1) The Kirchoff hypothesis of beam bending is adopted implying a linear distribution of strain within the depth of the beam section;

(2) Perfect bond between reinforcement and concrete is assumed. Reinforcement slippage occurring at advanced stress-strain states is included into $\sigma - \varepsilon$ curve of tensile concrete.

(3) The constitutive model is based on a smeared crack approach, i.e. average stresses and strains are used.

(4) All fibres in the tensile concrete zone follow the same stress-strain law. Similarly, this is also applied to the fibres of the compressive zone.

The latter assumption is less accurate for tensile concrete since for the given constant strain in the cracked concrete, fibres close to the reinforcement carry larger average stresses than fibres more distant from that reinforcement (Fig 3).

3. Basic geometrical and equilibrium equations

Consider a non-prestressed doubly reinforced concrete member subjected to bending only. A cross-section for such member is presented in Fig 4. Curvature can be determined from strains for two different fibres. Since the experimental data often include values for the average strains at the extreme concrete fibre for both compression and tension or for the extreme concrete fibre in compression and the tension steel for

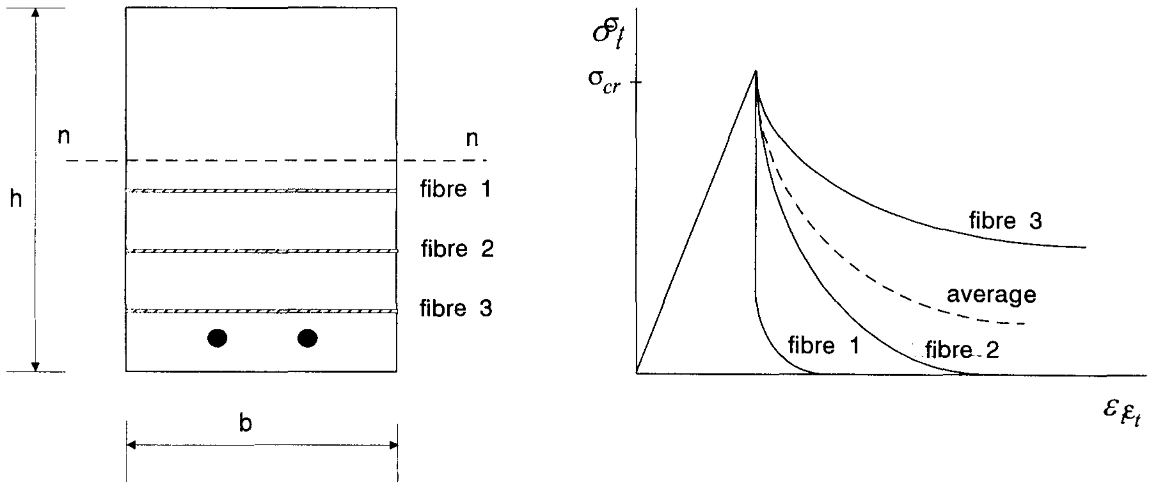


Fig 3. Average stress-strain relation for concrete in tension for different layers of a cross-section

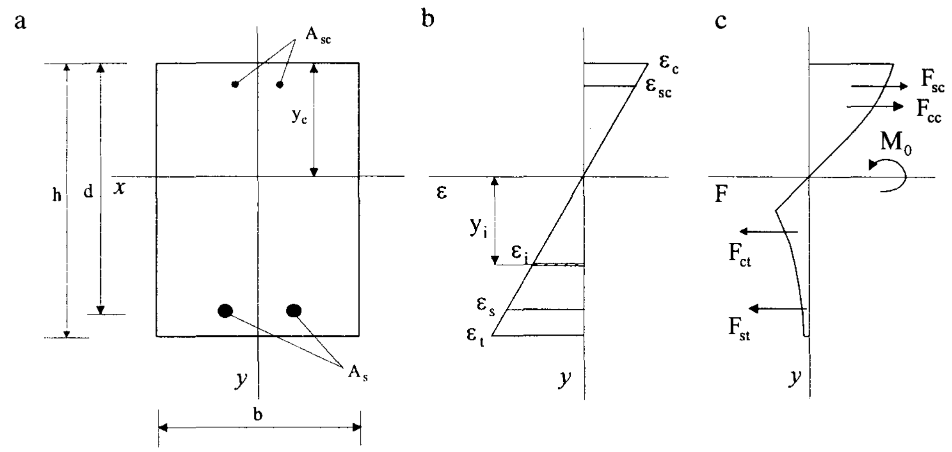


Fig 4. Reinforced concrete section subjected to bending moment. (a) - a doubly reinforced section; (b) - strain compatibility; (c) - internal forces and external bending moment

tension, curvature, κ, can be expressed as

$$\kappa = \frac{\varepsilon_t - \varepsilon_c}{h} \tag{1}$$

or

$$\kappa = \frac{\varepsilon_s - \varepsilon_c}{d} \tag{2}$$

where ε_c, ε_t are average strains at extreme concrete fibres in compression and tension respectively; ε_s is average tensile reinforcement strain; and h and d are the overall depth and effective depth of the cross-section respectively.

The location of the neutral axis can be defined by:

$$y_c = \frac{\varepsilon_c}{\varepsilon_t - \varepsilon_c} h = \frac{\varepsilon_c}{\varepsilon_s - \varepsilon_c} d \tag{3}$$

and from strain compatibility considerations, the strain at any fibre can be expressed as:

$$\varepsilon_{x,i} = \kappa y_i \tag{4}$$

where y_i is the distance of the fibre from the zero strain surface. The sign convention adopted is that tension, extension, and distance below the neutral axis are positive.

From equilibrium

$$F_{cc} + F_{sc} + F_{ct} + F_{st} = 0 \tag{5}$$

$$M_{cc} + M_{sc} + M_{ct} + M_{st} - M_0 = 0 \tag{6}$$

where F are internal forces, M are internal moments in respect of the neutral axis, and M_0 is the external bending moment.

The first subscript corresponds to either c for concrete or s for steel and the second subscript refers to compression (c) or tension (t). The sign of the force F is the same as for the corresponding strain $\varepsilon_{x,i}$.

4. Proposed method for determination of stress-strain curves

This work is aimed at determining average material stress-strain, $(\sigma-\varepsilon)$, curves for concrete from experimental data for reinforced concrete beams or one-way slabs subjected to bending moment. The experimental data used can be as follows:

(a) moment-average strain relation for extreme fibre of compressive concrete;

(b) moment-average strain relation for extreme fibre of tensile concrete;

(c) moment-average strain relation for tensile reinforcement;

(d) moment-average curvature relation;

(e) reinforcement steel stress-strain relation.

Consider a case when relations (a), (b), and (e) are available. Then, the location of the neutral axis and average strains at any fibre for all loading stages can be determined from eqs (1), (3), and (4). Two equilibrium equations (5) and (6) can be solved for each loading stage yielding a solution for two unknowns. A layered model can be conveniently employed for computation of internal forces in the cross-section. Stresses and internal forces in the reinforcing bars can be determined from the longitudinal strains using reinforcement $\sigma-\varepsilon$ curves. Since the external moment M_0 is known, average stresses for the tensile and compressive concrete zones could be the two unknowns in the equilibrium equations (5) and (6). However, there are many fibres (layers) in both the tensile and compressive concrete zones and the variation in stresses in each of these zones is not known.

A simple concept, based on the assumption of constant material stress-strain relations, allows the reduction of the number of unknowns to one for each zone. The equilibrium equations are solved for concrete stresses at extreme fibres. Since the extreme fibres have the highest strains, all other fibres have lower strains, and therefore fall within the portion of the stress-strain diagram which has already been determined.

Computation is performed for incrementally increasing load. During the first load stage, tensile and compressive concrete stresses corresponding to the strains in the extreme fibres are computed. These stresses are then used in the equilibrium equations for the second load stage when new stresses corresponding to larger extreme fibre strains are determined. In this way, stress-strain curves for the tensile and compressive concrete are progressively obtained from all previous stages and used in the next load stage.

The proposed method is illustrated in Fig 5 and 6. It is assumed that the "experimental" moment-average strain curves for extreme fibres of the compressive and tensile concrete are given, as in Fig 5(a) and (b) respectively. Circled points in these curves correspond to experimental data. Simple linear connection of experimental points would give discontinuous moment-strain curves. Naturally, the material $\sigma-\varepsilon$ relations computed for such curves are expected to have jumps at points of slope discontinuity leading to an overall oscillating shape. MATLAB [12] was used in the present work to smooth the $M-\varepsilon$ curves resulting in the solid lines in Fig 5 (a) and (b). Computation is performed for an assumed number of load increments equal to n. In order to avoid oscillations in the computed material $\sigma-\varepsilon$ curves, n has to be sufficiently large. For most practical cases, $n > 50$ is sufficient and $n = 100$ has been used in the present work.

The size of moment increment is:

$$\Delta M = M_{\max}/n \tag{7}$$

and the moment at load increment i is:

$$M_i = i \cdot \Delta M \tag{8}$$

where $M_{\max}$ is the maximum moment value for the $M-\varepsilon$ curves.

Strains at the extreme fibre of the concrete compressive zone, [Fig 5(a)]

$$\varepsilon_{c,i} = \varepsilon_{c,1}, \varepsilon_{c,2}, \ldots, \varepsilon_{c,n-1}, \varepsilon_{c,n} \tag{9}$$

and the tensile zone, [Fig 5(b)]

$$\varepsilon_{t,i} = \varepsilon_{t,1}, \varepsilon_{t,2}, \ldots, \varepsilon_{t,n-1}, \varepsilon_{t,n} \tag{10}$$

corresponding to moment

$$M_i = M_1,\ M_2 \ldots\ldots M_{n-1},\ M_n \tag{11}$$

are determined numerically for the smoothed curves.

A layered model with a constant number of layers could be employed for this problem. However, for visualization purposes and simplification of the solution, an approach based on an increasing number of concrete layers was introduced in the present work. The number of concrete layers in both compressive and tensile zones was assumed to be equal to the load increment number i. Thickness variation of the con-

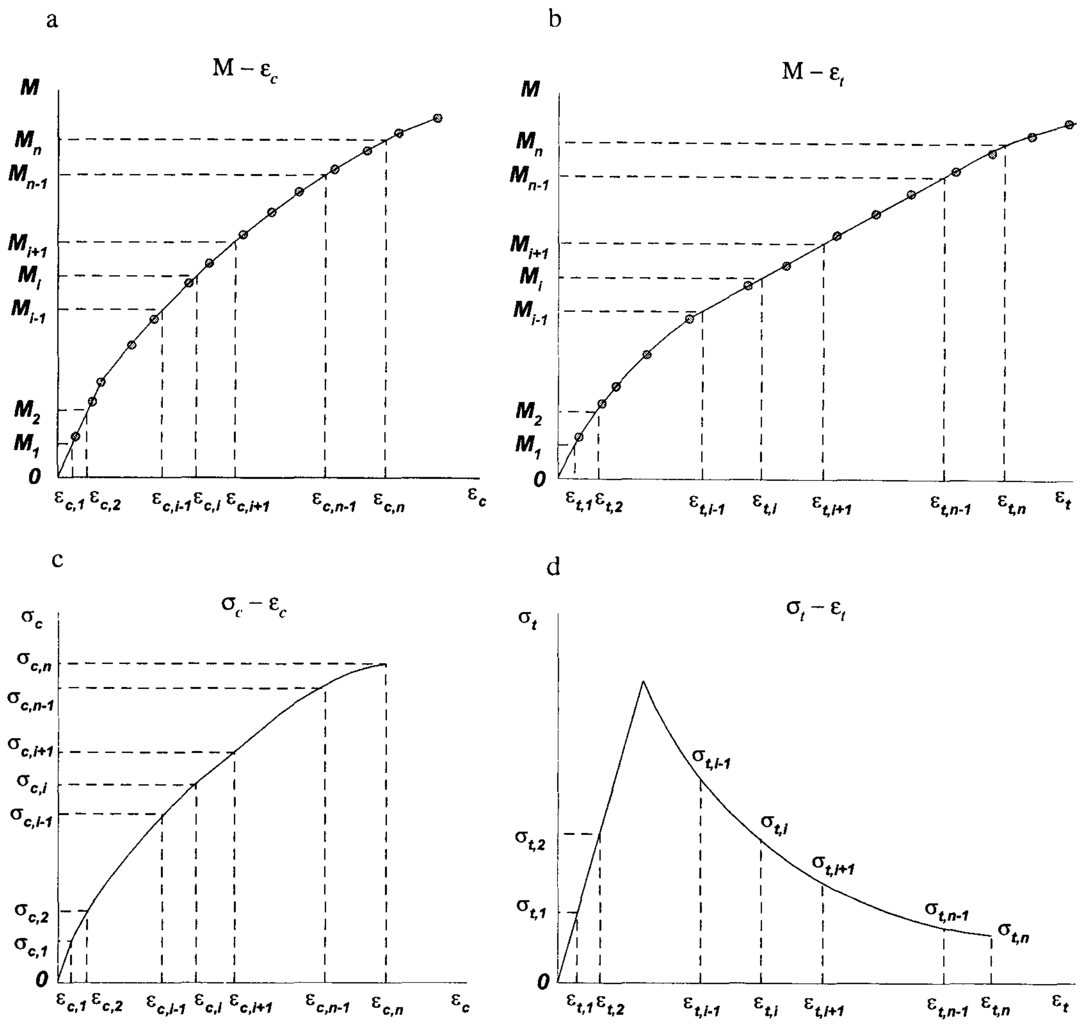


Fig 5. "Experimental" moment-curvature curves and computed stress-strain relations for concrete

crete layers in the compressive zone is assumed from the condition that extreme fibres of the 1st, 2nd and i-th layer acquire strains from (9) $\varepsilon_{c,1}$, $\varepsilon_{c,2}$ and $\varepsilon_{c,i}$ respectively. Similarly in the tensile zone extreme fibres of the 1st, 2nd and i-th layer acquire strains from (10) $\varepsilon_{t,1}$, $\varepsilon_{t,2}$ and $\varepsilon_{t,i}$ respectively. In common case the thickness of the layer j for the compressive zone is taken as:

$$t_{c,j,i} = y_{c,i}\left|\frac{\varepsilon_{c,j} - \varepsilon_{c,j-1}}{\varepsilon_{c,i}}\right| \qquad (12)$$

and for the tensile zone as:

$$t_{t,j,i} = (h - y_{c,i})\frac{\varepsilon_{t,j} - \varepsilon_{t,j-1}}{\varepsilon_{t,i}} \qquad (13)$$

where $\varepsilon_{c,j}$, $\varepsilon_{t,j}$ are the strains of the extreme fibers of the layer j in the compressive and tensile zone respectively, $y_{c,i}$ is the depth of the compressive zone at load increment i and the variation in layer numbers is due to $j \le i$, $j = 1, 2, ..., i$ and $i = 1, 2, ..., n$.

In expressions (12) and (13) the subscript c refers to compressive concrete, t - to tensile concrete, i - to the number of the load increment, and j - to the layer number.

Since the number of layers increases with each load increment, the thickness of each layer decreases. This assumption for the number of concrete layers in a cross-section together with the corresponding strains and stresses is presented in Fig 6. For load increment $i = 1$ [Fig 6(b)], one layer is assumed for each concrete zone. The extreme fibre strains for the compressive and tensile concrete layers are $\varepsilon_{c,1}$ and $\varepsilon_{t,1}$ respectively. From the equilibrium equations, the corresponding stresses $\sigma_{c,1}$ and $\sigma_{t,1}$ are computed. For load increment $i = 2$, [Fig 6(c)], two layers are assumed for each concrete zone. Both strains and stresses are known for the top fibres of the first layers

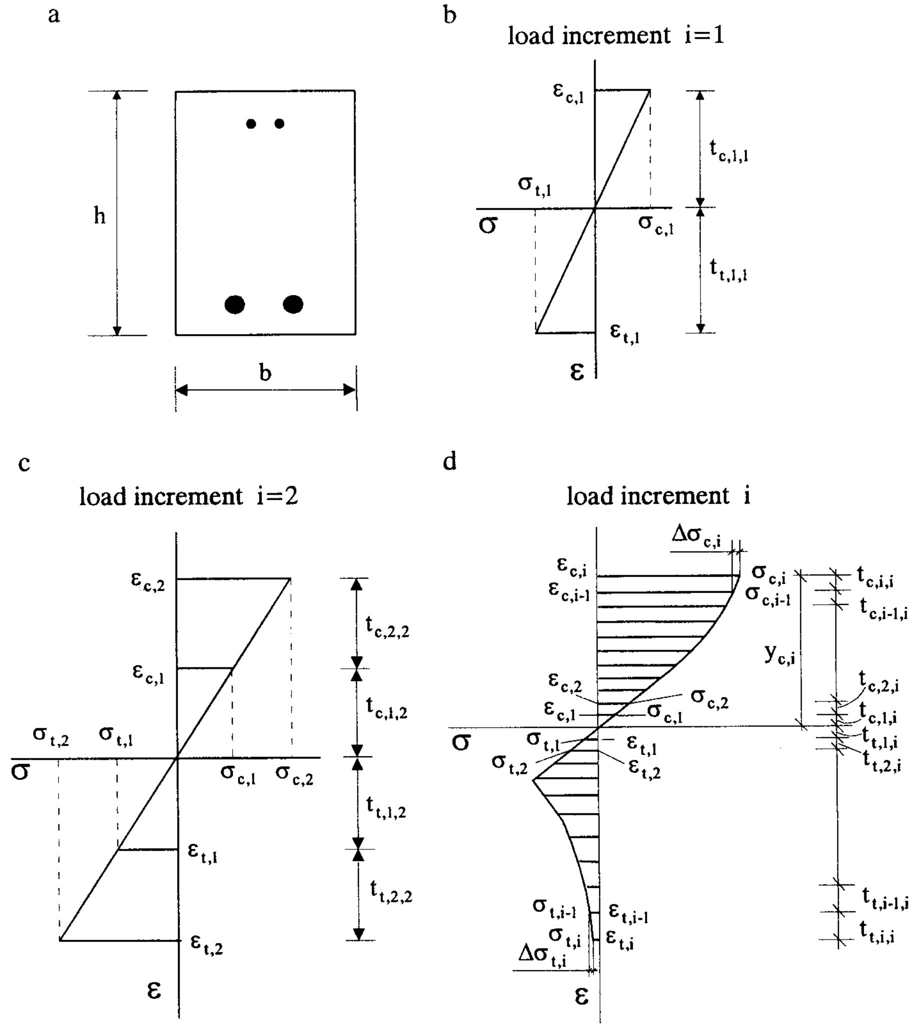


Fig 6. Stresses and strains and concrete layer assumption in a cross-section for different load stages

(j = 1) since $\varepsilon_{c,1}$, $\sigma_{c,1}$ and $\varepsilon_{t,1}$ and $\sigma_{t,1}$ are the same as for i = 1. The top fibre strains for the second layers (j = 2) are $\varepsilon_{c,2}$ and $\varepsilon_{t,2}$. The corresponding stresses $\sigma_{c,2}$ and $\sigma_{t,2}$ are computed from the two equilibrium equations.

The case for load increment i is shown in Fig 6(d). For computation of $\sigma_{c,i}$ and $\sigma_{t,i}$ at load increment i, equilibrium equations (5) and (6) are rearranged so that values for F_{cc}, F_{ct}, M_{cc} and M_{ct}, corresponding to the internal forces and moments for the concrete, are divided into two components each:

$$F_{cc,i-1} + \Delta F_{cc,i} + F_{sc} + F_{ct,i-1} + \Delta F_{ct,i} + F_{st} = 0 \quad (14)$$

$$M_{cc,i-1} + \Delta M_{cc,i} + M_{sc} + M_{ct,i-1} + \Delta M_{ct,i} + M_{st} + M_0 = 0 \quad (15)$$

where $F_{cc,i-1}$, $F_{ct,i-1}$, $M_{cc,i-1}$, and $M_{ct,i-1}$ are internal concrete forces and moments due to all corresponding zone concrete layers except the extreme layers ($j = 1,2 \ldots i-1$); and $\Delta F_{cc,i}$, $\Delta F_{cc,i}$, $\Delta M_{cc,i}$, and $\Delta M_{ct,i}$ are the forces and moments for the extreme layers $j = i$.

At load increment i, components $F_{cc,i-1}$, $F_{ct,i-1}$, $M_{cc,i-1}$, and $M_{ct,i-1}$ can be fully determined since the compressive and tensile stresses in concrete layers $j = 1,2 \ldots i-1$ are known. The remaining four concrete force and moment components can be expressed by stress increments $\Delta\sigma_{c,i}$ and $\Delta\sigma_{t,i}$ [Fig 6 (d)] in the extreme fibres:

$$\Delta F_{cc,i} = bt_{c,i,i}\left(\sigma_{c,i-1} + \frac{1}{2}\Delta\sigma_{c,i}\right) \quad (16)$$

$$\Delta M_{cc,i} = bt_{c,i,i}\left[\sigma_{c,i-1}\left(y_{c,i} - \frac{1}{2}t_{c,i,i}\right) + \frac{1}{2}\Delta\sigma_{c,i}\left(y_{c,i} - \frac{1}{3}t_{c,i,i}\right)\right] \quad (17)$$

$$\Delta F_{ct,i} = bt_{t,i,i}\left(\sigma_{t,i-1} + \frac{1}{2}\Delta\sigma_{t,i}\right) \tag{18}$$

$$\Delta M_{ct,i} = bt_{t,i,i}\left[\sigma_{t,i-1}\left(h - y_{c,i} - \frac{1}{2}t_{t,i,i}\right)\right.$$

$$\left.+\frac{1}{2}\Delta\sigma_{t,i}\left(h - y_{c,i} - \frac{1}{3}t_{t,i,i}\right)\right]. \tag{19}$$

Equilibrium equations (14) and (15) are solved explicitly for $\Delta\sigma_{c,i}$ and $\Delta\sigma_{t,i}$. Then concrete stresses $\sigma_{c,i}$ and $\sigma_{t,i}$ for load increment i are easily defined from

$$\sigma_{c,i} = \sigma_{c,i-1} + \Delta\sigma_{c,i}, \tag{20}$$

$$\sigma_{t,i} = \sigma_{t,i-1} + \Delta\sigma_{t,i}. \tag{21}$$

Using values of the computed stress ($\sigma_{c,i}$ and $\sigma_{t,i}$) and the corresponding strains ($\varepsilon_{c,i}$ and $\varepsilon_{t,i}$), step by step stress-strain curves for concrete in compression and tension [Fig 5(c) and (d)] are constructed.

Special arrangements can be made to assess net concrete area due to the presence of reinforcement.

5. Numerical verification

The proposed method has been tested on a numerical example. The test procedure is described in the following. Consider a fully defined cross-section of a reinforced concrete member with assumed stress-strain relations for reinforcing steel and both compressive and tensile concrete. First, moment-strain relations have to be generated. Next, from these moment-strain relations, material stress-strain relations for both compressive and tensile concrete are computed by the proposed method. The test is considered successful, when the initially assumed and computed material $\sigma - \varepsilon$ relations coincide.

The cross-section and physical-mechanical properties of the beam chosen for this validation test are shown in Fig 2(a). The stress-strain relation presented in Fig 1 is assumed for the tensile concrete ($\alpha_1 = 1$ and $\alpha_2 = 20$). The stress-strain relation for the compressive concrete is assumed to be as follows:

$$\sigma_c = f_c'\left[2\frac{\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right] \tag{22a}$$

where

$$\varepsilon_0 = 2f_c'/E_c \tag{22b}$$

Here σ_c and ε_c are the stress and strain respectively of the compressive concrete; and f_c' and ε_0 are the maximum compressive stress and the corresponding strain for standard cylinder test. Though both values in computations are taken as negative, the sign minus is omitted in the text.

A special program was developed for stress-strain and curvature computation of a layered cross-section with non-linear material properties. Moment-strain diagrams $M-\varepsilon_c$, $M-\varepsilon_t$ and $M-\varepsilon_s$ for the extreme concrete fibres and tensile reinforcement respectively shown in Fig 7(a) and moment-curvature ($M-\kappa$) diagram shown in Fig 7(b) were generated. From the $M-\varepsilon_c$ and $M-\varepsilon_t$ diagrams, stress-strain relations for tensile concrete ($\sigma_t - \varepsilon_t$) and for compressive concrete ($\sigma_c - \varepsilon_c$) were computed by the method described here. The corresponding relations are plotted along with the assumed relations in Fig 8. It can be seen that the agreement is good and therefore the

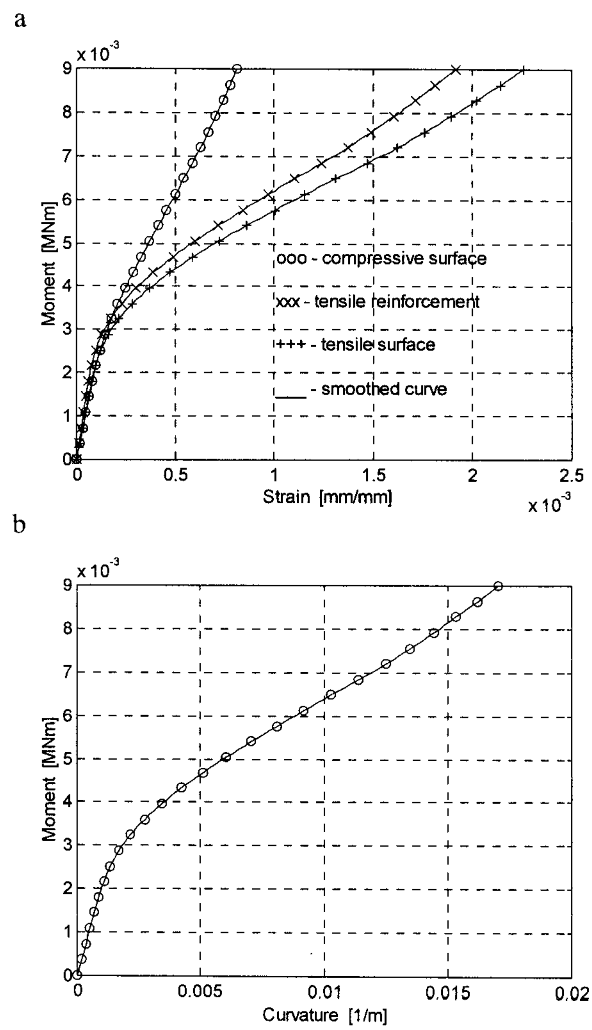


Fig 7. Assumed moment-strain (and curvature) relationships in the numerical test (a) - moment-strain curves; (b) - moment-curvature curve

proposed method can be used to establish reasonable stress-strain relations from beam or slab data.

6. Conclusions

A new method for determining the stress-strain relations for concrete from flexural tests of reinforced concrete members was proposed. For given experimental moment-curvature and moment-strain curves, the material stress-strain relations are computed for incrementally increasing moment assuming portions of the relations obtained from the previous increments. The method allows to determine the average stress-strain relations for concrete in tension and compression including the descending part of the curves. The computation does not require information about concrete properties. The proposed method has been tested numerically.

a

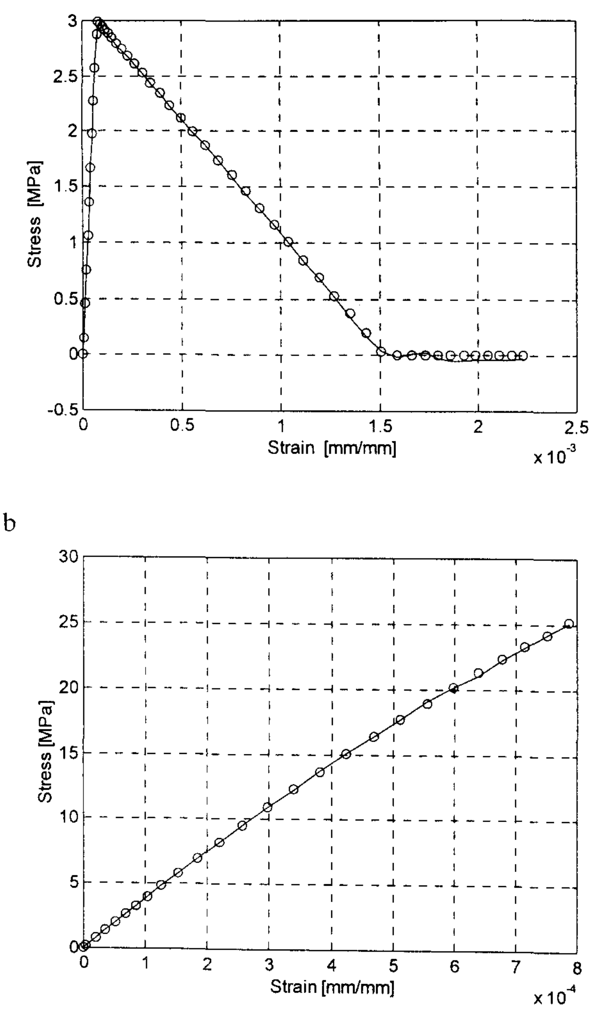


Fig 8. Comparison of initially assumed and computed concrete stress-strain relations. (a) - for tensile concrete (b) - for compressive concrete.
oooo - initially assumed; ______ - computed

As a development of the method, practical techniques assessing scatter of the experimental data are intended to be proposed and applied to actual experimental data. This will be the subject of subsequent publications.

Acknowledgments

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METODAS BETONO ĮTEMPIMŲ-DEFORMACIJŲ DIAGRAMOMS NUSTATYTI IŠ LENKIAMŲJŲ GELŽBETONINIŲ ELEMENTŲ EKSPERIMENTINIŲ DUOMENŲ

G.Kaklauskas

S a n t r a u k a

Pasiūlytas naujas skaičiavimo metodas vidutinių betono įtempimų-deformacijų diagramoms nustatyti, naudojant lenkiamųjų gelžbetoninių elementų eksperimentų duomenis. Turint eksperimentines momentų-kreivių ir momentų-deformacijų diagramas gaunama visa tempiamo betono vidutinių įtempimų-deformacijų diagrama, įskaitant ir jos krentančiąją dalį. Taip pat, net neturint duomenų apie betono savybes, galima pakankamai tiksliai rasti ir gniuždomo betono diagramą. Skaičiavimas pagrįstas nauja idėja, kai tempiamo ir gniuždomo betono įtempimų-deformacijų diagramos skaičiuojamos kraštiniams lenkiamo elemento sluoksniams. Turint eksperimentines kraštinių sluoksnių deformacijas kiekvienai apkrovos pakopai randami tų sluoksnių įtempimų prieaugiai. Kiekvienoje apkrovos pakopoje gautos diagramos taikomos kitiems mažiau deformuotiems sluoksniams. Pasiūlytasis metodas patikrintas skaičiavimais.

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