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Constitutive Models for Design of Sustainable Concrete Structures

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Abstract. The paper deals with numerical models of reinforced concrete which are expected to be useful to enhance design of sustainable reinforced concrete structures. That is, the models which can deliver higher precision of results than the linear elastic models but which are still feasible for engineering practice. Such models can be based on an elastic-plastic material. The paper discusses properties of such models. A material model based on the Chen criteria and the Ohtani hardening model for concrete was selected for further development. There is also given a comparison of behaviour of such model with behaviour of a more complex smeared crack model which is based on principles of fracture mechanics.

1. Introduction

Large number of buildings in Europe (and also in other areas) is still based on reinforced concrete structures. There are many efforts to replace the traditional components of concrete by their renewable alternatives or by alternatives obtained by waste recycling processes. Even if we take into account these developments then the concrete still has to be considered as a material which in not easily renewable nor prepared from renewable sources. Thus there are obvious needs to limit its use as much as possible. So sustainable concrete should be used. By the term sustainable concrete, we mean concrete which not only uses secondary materials (slag in this case) instead of non-renewable ones as much as possible but which has long service life.

One of the possible approaches is use of advanced numerical models in the design phase. A high-quality numerical modelling can allow to design structures which should use as little concrete as possible. The most common structural design approach in the civil engineering is still use of linear elastic modelling for analysis of static and dynamic behaviour of bearing structure. Such approach is correct and it is recommended by current technical standards (the Eurocodes in Europe and other countries, for example). But these technical standards also allow to use more up-to-date approaches which should include, among others, assumptions of non-linear material behaviour. It is obvious that increased precision of material modelling should allow to predict more precisely the necessary amount of material and thus it should lead to more effective design.

The paper concentrates on models which should be compatible with author's effort on development of finite element code for design of reinforced concrete structures with enhanced modelling of soil-structure interaction. The developed algorithms are meant to improve numerical modelling on structural level and not only on level of individual structural members. Use of non-linear material models in combination of an additional non-linearity (the soil-structure interaction is a non-linear problem)
requires to use algorithms which can be executed in parallel. Such approach can considerably speed-up the computations but it also defines further limitations for numerical models. [1]

2. Considerations

Design of structures like living houses and administrative objects should not allow to expose the used materials to load effects which may cause their progressive damage. For example, there has to be no plastic behaviour of steel structural members (except some special cases like behaviour of bolts and other connecting elements).

In the case of reinforced concrete there should be no progressive cracking nor crushing and material should not excess its peak bearing capacity. It is obvious that such behaviour should not occur in any stage of normal use of such objects.

Thus in macroscopic scale there should be no measurable softening. Obviously, on micro-level the cracking of concrete is inevitable. But presence of reinforcement should prevent the softening of the global reinforced concrete material. That it can be assumed that reinforced concrete structures of living and administrative objects can be designed with use of elastic-plastic material models which usually cannot model softening of material. There are of course exceptions, there are special cases when even more precise models are necessary: objects of high importance have to be designed to endure progressive damages caused by extraordinary loads (explosions, extensive fire and so) and in these cases more precise numerical models, which have to include softening effects [2] or visco-plastic behaviour, have to be used.

3. Material modelling

There are many computational models which utilise elastic-plastic material model. Some of them are implemented in well-known software packages (models by Willam and Warnke [3] or by Lee and Fenves [4], for example), some other models are often used in academic program codes (Chen [5], one of the modifications of the Chen model has been implemented by authors of this article [6]). All these models are represented by very similar plasticity conditions (see Figure 1 for an illustration).

![Figure 1](image)

**Figure 1.** Typical shape of plasticity condition for concrete in principal stresses plane in 2D.

There are more advanced approaches which usually utilise approaches of fracture mechanics. [2] Those solutions often allow to simulate softening behaviour of concrete, sometimes at a cost of simplified modelling of undamaged material behaviour. The most basic approach is the smeared crack model [2]. It uses an assumptions that damaged concrete can be modelled as an orthotropic (or even anisotropic) material with different properties in different material axes. These axes are oriented in accordance with cracks direction. These models are known to be prone quality and size to finite element meshes and there are many approaches how to eliminate this issue [2]. One of the most common ways is to introduce additional material parameters, e.g. fracture energy [7].
In many cases material models use some combination of an elastic-plastic approach (which is used in initial stages of material behaviour) and the smeared crack approach (which is used for damaged material).

4. Elastic-plastic and smeared cracks material models
The authors of this paper have implemented a material model based on the Chen [5] plasticity and failure conditions. The model assumes an elastic-plastic material behaviour. Plastic behaviour is modelled as a hardening with different hardening functions for different stress states of material (uniaxial compression, bi-axial compression, uniaxial tension). These functions are implemented by means of approximation by Ramberg-Osgood function [8].

![Figure 2. Smeared crack model basic principle.](image)

The second model discussed here is a fracture mechanics based one. The assumptions are similar to [9]. The initial material properties are linear elastic. Material with cracks is modelled as orthotropic and its material axes depend on global cracks directions. But the area where the cracks are simulated remains to be continuous (Figure 2). The material axes directions (Figure 3) are obtained from orientation of principal stresses in the moment of crack initiation. This material model is a subject to finite element mesh-dependent behaviour. Thus the crack band model approach by Bazant [2] is used here. Due to nature of the model which does not simulate material softening it is possible to use the fairly simple Newton-Raphson non-linear computational procedure here.

This material model uses softening and it can result in softening on a structural level. Thus the computational strategy based on the Arc-Length method [10] is used in computations of these models.

![Figure 3. Material axes of smeared crack model.](image)

5. Comparison of models behaviour
The first case that we are showing in this paper is a numerical simulation of four-point bending test of concrete beam. It was modelled with use of an elastic-plastic model described above (Figure 4) and the model based on fracture mechanics (Figure 5).

Both models can give comparable load-displacement curve below the peak of bearing capacity is reached. Even the area affected by non-linear material behaviour is very similar - the elastic-plastic model proposes larger affected area for the same level of deformations. Obviously, the elastic-plastic
model cannot simulate post-beak behaviour (the process of material softening) which is thus only shown for the second model in Figure 5.

Figure 4. Plastic areas (red shades) of elastic-plastic model.

Figure 5. Development of area damaged by tension cracking.
The second model is a slender reinforced concrete arc of height 2 m. It was modelled with use of both abovementioned models. The Figure 6 shows areas where plasticity developed and the Figure 7 compares load-displacement curves obtained from these models. It is obvious that the elastic-plastic model dives more optimistic assumption of bearing capacity of the arc.

![Figure 6. Plastic areas on arc model.](image)

![Figure 7. Comparison of elastic-plastic (red) and smeared crack (green) behaviour of the arc.](image)
It is worth to mention that the smeared crack model required near 5-10x longer computational time than the elastic-plastic model with the same finite element mesh. Both discussed models used minimal reinforcement ration and thus they are not the most typical examples of reinforced structure design but they are rather limit cases for such problems. For higher reinforcement ratios the result will be even better in favour of the elastic-plastic model.

6. Conclusions
The abovementioned examples illustrate that elastic-plastic models material can be used for more precise modelling of reinforced concrete structures. However, some points have to be taken into account: The assumption must be valid that the designed structure must not be exposed to progressive damage in any part of its lifetime.

The elastic-plastic models (even these which are included in commercial software packages) are dependent on size and shape of finite element meshes. Thus is is necessary to validate the input data on a numerical re-modelling of a basic material test of the actual reinforced concrete sample (a four-point bending test can be used here). The dependence of finite element mesh parameters can be minimised by using the same size (and shape) of finite elements both in model of such test and for the actual model of the designed structure.

For such reasons it can be stated that elastic-plastic models can be used as a basis for non-linear material modelling of reinforced concrete structures in the cases of sustainable buildings design.

7. References
[1] Fialko S 2015 Comp. and Math. with Appl. 70, 2968–87
[2] Jirasek M and Bazant Z P 2002 Inelastic Analysis of Structures (Chichester: John Willey and sons)
[3] Willam K J and Warnke E P 1975 Int. Assoc. Bridge Struct. Eng. Proc. 35, 1-30
[4] Lee J and Fenves G. L. 1998 J. Eng. Mech. 124, 892-900
[5] Ohtani Y and Chen W. F. 1988 Journal of the EDM ASCE. 114 L11
[6] Brozovsky J and Krejsa M 2017 Key Engineering Materials. 738, 319-28
[7] Karihaloo B L 1995 ‘Fracture Mechanics and Structural Concrete’ (Essex: Longman Group Limited)
[8] Sucharda O and Brozovsky J 2014 Fratt. ed Integ. Strutt. 30, 375-82
[9] Cervenka V 1985 Constitutive Model for Cracked Reinforced Concrete. 82 L6
[10] Riks E 1979 Int. J. Solids Struct. 15 524-51

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