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INSTABILITY OF REINFORCED CONCRETE CONTAINMENT UNDER INTERNAL PRESSURE

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ABSTRACT

In analysis of reinforced concrete containment of nuclear power plant some difficulties often occur in definition of equilibrium state near the point of cracking. It may be shown that these difficulties are not connected with imperfection of algorithms. They are caused by the nature of reinforced concrete. Forces, carrying by concrete part of section, abruptly decrease at cracking. Disbalancement occurs between internal and external forces, acting in section. Later this disbalancement may be compensated by growth of forces in reinforcing. However at some reinforcing ratio and mechanical properties of materials this growth may go more slowly then decreasing of forces in concrete. As a result a zone of temporary fall of bearing capacity of section develops on deformation curve. Equilibrium in this zone at steady growth of load is statically impossible. This zone can be passed only in dynamic regime - by jump across it. In the physical and mathematical sense this phenomenon is analogous to well known «instability in small» of cylindrical shells under ax[al compression. Criterion of this form of instability is given in this paper.

Keywords: containment, concrete, reinforcing, cracking, instability.

1. INTRODUCTION

Conventional analysis of reinforced concrete deals with the limit state of the section. Such analysis does not consider how this limit state was reached in the process of loading. This approach may be successfully used in analysis of beams, columns and other beam constructions, where the type of limit state is predetermined. It can not be used in analysis of spatial constructions, such as containments of nuclear power plant (Fig.1), especially in nonlinear analysis with simulating of failure of construction. In such analysis modification of structural model must be simulated as a result of steadily failure and off-loading of high stressed zones of construction.

In such cases the modern approach to analysis of reinforced concrete should be used. This approach traces the development of failure zones of construction using general principles of mechanics. Specific features of reinforced concrete are introduced by input of appropriate constitutive laws for concrete and reinforcing. As a result efficient apparatus of finite element method (FEM) can be used for analysis of reinforced concrete. In couple with load-incremental method it allows to treat reinforced concrete as a nonlinear material. This approach is used in commercial codes for analysis of reinforced concrete, such as Western MARC, ADINA, ABAQUS and East-European FENIX, PUSK.

Practical using of this apparatus, however, showed, that some difficulties may occur when finding the equilibrium states of construction at the level of loading, which corresponds to the point of cracking of concrete.

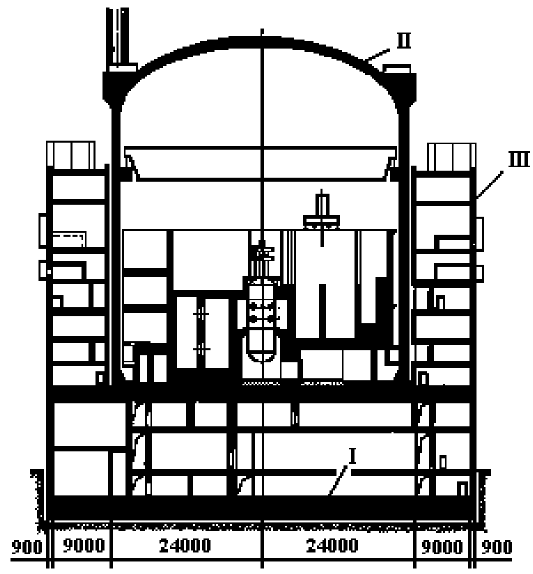

Fig.1. Reactor building of nuclear power plant. I-basement, II-containment, III-external constructions

2. EQUILIBRIUM OF TENSIONED REINFORCED CONCRETE

To understand the nature of this difficulties let us consider the equilibrium curve for tensioned horizontal strip of containment wall. Section of this strip is shown in Fig.2 a. Tension in containment wall occurs for example at inner pressure loading, which is the main design case for containment. Really containment wall is in the state of biaxial tension with relation of components

$$\sigma_1 / \sigma_2 = 1/2\,,$$

but for simplifying the analysis let us assume $\sigma_2 = 0$ i.e. the wall is considered as being in the state of uniaxial tension.

As in many computer codes real section of the wall with rebars may be modeled as a layered one by smearing of reinforcing in appropriate layers (Fig. 2 b).

Then longitudinal force in the wall

$$N = \sigma_c t_c + (\sigma_{s1} t_{s1} + \sigma_{s2} t_{s2})\,, \qquad (1)$$

where σ_c - average stress in concrete, σ_{si} - stress in i-th layer of reinforcing.

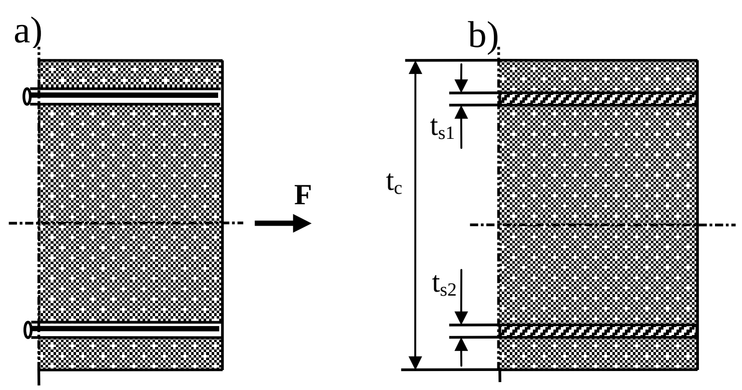

Fig.2. Section of a horizontal strip of containment wall a – real (reinforced), b – equivalent (layered)

In the case of symmetric section

$$\sigma_{s1} = \sigma_{s2} = \sigma_s$$

and

$$N = \sigma_c t_c + \sigma_s t_s\,, \qquad (2)$$

where $t_s = t_{s1} + t_{s2}$.

Tracing the process of loading, we should consider the stresses as a functions of achieved strains:

$$\sigma_c = \sigma_c(\varepsilon), \qquad (3)$$

$$\sigma_s = \sigma_s(\varepsilon). \qquad (4)$$

In present work function (3) was used in the form of Prandtl diagram (Fig.3). For function (4) experimental diagram of concrete B30 (Fig.4) was used. No reliable experimental results are available for strains more then $300{\cdot}10^{-6}$. This branch of softening curve was adopted as linear with $\sigma_c = 0$ at yielding strain of reinforcement $\varepsilon_y = 2{\cdot}10^{-3}$.

Using these diagrams longitudinal force $N(\varepsilon)$ which the section of the strip can bear at given strain may be expressed as a function of strain. This function is sown in the Fig.5.

Characteristic feature of this function is the local maximum of the force N near the point of cracking A. It occurs because rigidity of concrete part of section declines after this point very quickly accordingly with large negative tangent modulus of concrete after cracking (branch **ab** of the curve of Fig.4). Capacity of the steel part of the section grows much more slowly in accordance with constant modulus of steel. This growth can compensate decline of capacity of concrete only when strain ε will develop enough.

Mathematically the origin of local maximum of capacity of section may be understood using Eq.(2). On the

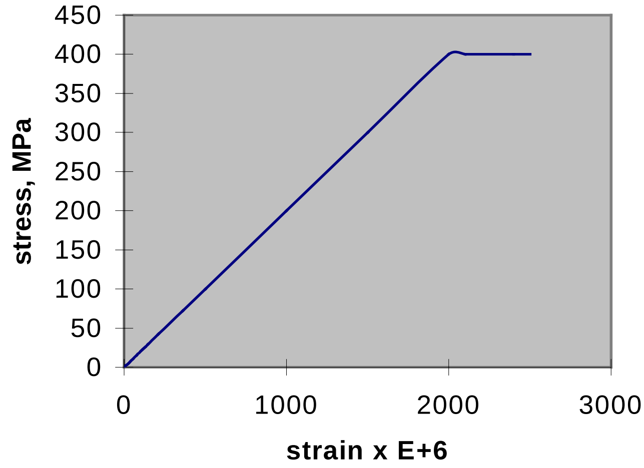

Fig3. Diagram of reinforcing steel

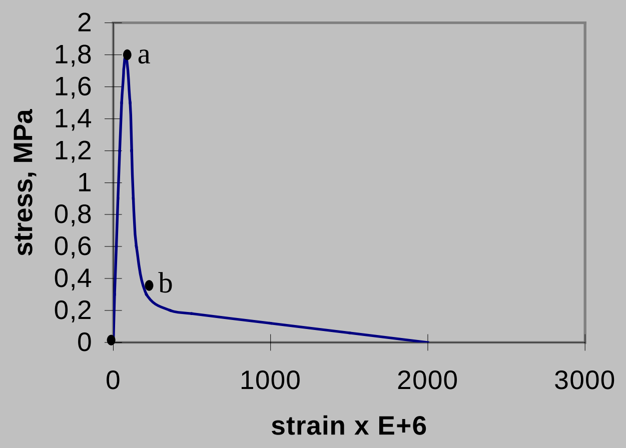

Fig4. Diagram of concrete B30 in tension

branch OA of Fig.5 both terms of Eq.(2) steadily grow. On the branch AB of curve 1 first term declines but second term continues to grow. However the growth of second term may be not enough to compensate decline of the fist term at little steel consumption t_s.

In experiment curve OABC may be realized only by cinematic loading. At force loading when force F steadily grows process will follow this curve only on the branch OA. For all states, represented by points lying on the branch ABC, at the assumed steel consumption longitudinal force N will be less then in point A. At loading by steadily increasing external force F these states will not satisfy condition of equilibrium

$$N = F. \qquad (5)$$

This condition can be satisfied only on the branch CD. Small increase of external force in point A will cause system to pass directly to branch CD of equilibrium curve. The states, lying on the branch ABC, at such loading are static impossible. System can pass over this zone only in dynamic regime - by jump AB_1C across it. In experiment this phenomenon must be seen as a jerk of reinforced concrete element at the level of tension, which corresponds to cracking. From the mathematical point of view the jump AB_1C may be assumed as a large increment of function (strain) at small increment of argument (force). According to Liapunov such behavior is a criterion of instability of system.

So both from physical and mathematical points of view behavior of reinforced concrete in tension is analogous to instability «in big», which is usual for some constructions, for example cylindrical shells under axial compression (Panovko, Gubanova, 1979). The range of strains, which corresponds to static impossible states of system at force loading may be defined as zone of instability.

3. CRITERION OF INSTABILITY

As analysis shows, zone of instability will appear not in all cases of tension of reinforced concrete. As was shown above the reason of instability is decline of capacity of section N. Condition of such decline may be defined as

$$\frac{dN}{d\varepsilon} < 0 \qquad (6)$$

Using Eq.(2) condition (6) may be written as

$$\frac{d\sigma_c}{d\varepsilon} < -\frac{t_s}{t_c}\frac{d\sigma_s}{d\varepsilon}$$

.

Assuming, that

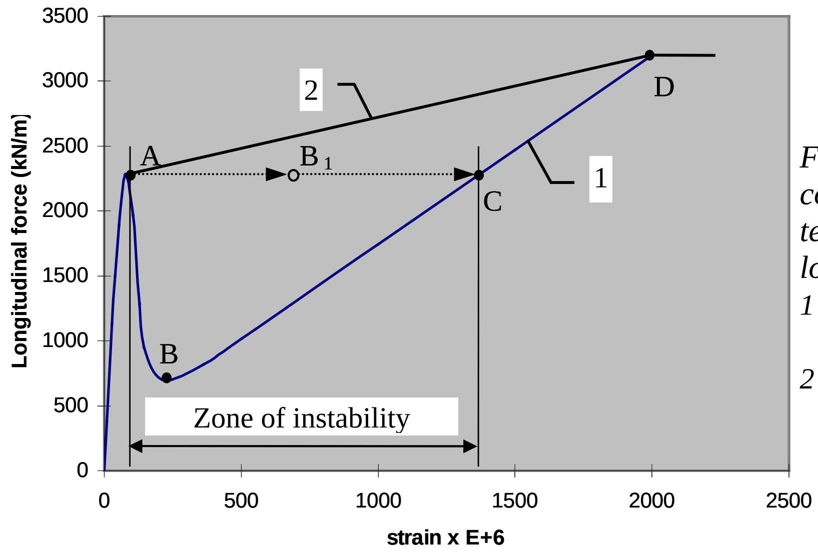

Fig.5. Bearing capacity of containment strip section in tension at different softening lows of concrete:
1 - experimental softening of pure concrete,
2 - linear softening

$$\frac{d\sigma_c}{d\varepsilon} = E_c(\varepsilon),$$

$$\frac{d\sigma_s}{d\varepsilon} = E_s(\varepsilon),$$

where

$E_c(\varepsilon)$ is the tangent modulus of deformation of concrete,

$E_s(\varepsilon)$ is the Young modulus of reinforcing steel (constant for adopted Prandtl diagram),

condition of instability of reinforced concrete strip in tension may be written as

$$E_c(\varepsilon) < -\frac{t_s}{t_c} E_s. \tag{7}$$

All terms in the right part of expression (7) are positive. So instability of concrete in tension may occur only if tangent modulus of concrete $E_c(\varepsilon)$ is negative, i.e. only at softening branch of concrete diagram. Expression (7) shows that this instability is the more probable the less is the steel/concrete ratio and the faster declines rigidity of concrete for adopted softening diagram.

Above described analysis may be applied not only to reinforced concrete but also to other composite materials. In this materials also may appear the phenomenon of tensile instability.

4. INFLUENCE OF SOFTENING CURVE

In above analysis diagram of pure concrete was used (Fig.4). However, presence of reinforcing may significantly change properties of concrete after cracking (Chen, 1982). Reinforcement involves concrete in tension between cracks. In analysis this phenomenon may be taken into account by some increasing of rigidity of concrete at softening branch of its diagram of tension. No common opinion exists now about softening curves, that would properly describe this phenomenon. Different types of softening curves were suggested by researchers based on their own experience. Some of proposed curves are shown in Fig.6. For all curves beginning of softening branch is set to strain ε_{cr} («cracking point»). All softening curves are set to zero at ε_y (yield strain of reinforcing steel). Some of these curves may smooth tensile instability of reinforced concrete and some of them may emphasis it.

Curve 1, proposed by H.F.Halvarsen (see ibid.), was used in some FEM programs for nonlinear analysis of reinforced concrete. This curve represents softening process by two linear branches, one of which is adopted to be vertical. For this branch tangent modulus of concrete $E_c \to -\infty$. Using criterion (7) we may conclude, that in this case instability will appear inevitably at any steel/concrete ratio.

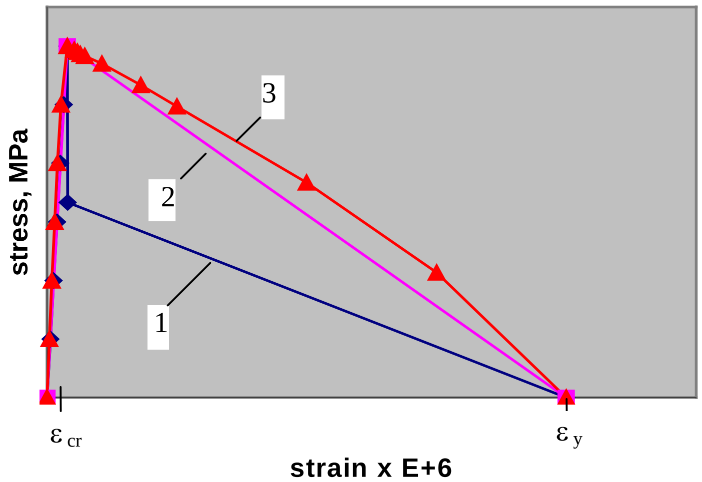

Fig6. Optional softening curves for concrete

Curve 2 represents linear softening, which is used as default option in ADINA (Bathe et al, 1989), MARC, ABAQUS and some other commercial program packages for nonlinear analysis of reinforced concrete. By using of this softening curve rate of decline of first term in Eq.(2) and rate of growth of second term are set to equivalence. In Fig. 5 curve 2 shows function of bearing capacity of section for this softening low. It may be seen, that in this case phenomenon of instability practically eliminates.

Some researchers suggest more sophisticated softening lows, connecting them with steel/concrete ratio and mechanical properties of materials. One of such lows was proposed by Del Grosso et al (1991). Curve 3 of Fig.6 represents this low for conditions of assumed containment section. It may be seen that this softening low gives decline of rigidity even less then in the case of linear softening. Using of this softening low will cause further increase of stability of reinforced concrete in tension.

5. CONCLUSIONS

Often instabilities, marked in analysis of tensioned reinforced concrete at cracking, are not connected with imperfection of algorithms. They may reflect real instability of reinforced concrete in tension. Forces, carrying by concrete part of section, abruptly decrease at cracking. As a result disbalancement occurs between internal and external forces, acting in section. If reinforcing ratio is enough forces carrying by steel part of reinforced concrete section will compensate this disbalancement but only after sufficient development of deformation. As a result a zone of strains occurs in which no static equilibrium of reinforced concrete may be achieved at force loading - the zone of instability. This zone can be passed only in dynamic regime - by jump across it. Phenomenon of tensile instability may occur not only in reinforced concrete but also in other composite materials. Analysis of conditions, in which this instability occurs, is performed and it’s criterion is given.

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