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# CLASSIC DAMAGE MODELS FOR REINFORCED CONCRETE: THEORY, APPLICATION, AND LIMITATIONS

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**The paper presents a review of damage models for reinforced concrete (RC) structures, analyzing their theoretical foundations, advantages, limitations, and fields of application. Four key models are considered: Continuum Damage Mechanics (CDM), damage-plasticity models (CDP), microplane models, and fatigue / accumulative damage models. Their performance is compared based on such criteria as the ability to describe stiffness degradation, universality of application, computational complexity, and prediction accuracy. In addition, practical parameters for numerical implementation are summarized, and the applicability of models to different tasks is outlined. The results of the review demonstrate that none of the models is universal. Ultimately, the study emphasizes the need for integrating physically based methods with modern digital technologies, which can expand the scope of damage models in industrial and civil construction.**

**Keywords: reinforced concrete, damage models, continuum damage model, damage–plasticity model, microplane model, fatigue damage model.**

## Introduction

Damage modeling of reinforced concrete (RC) structures is a crucial task of modern engineering mechanics. The availability of accurate and reliable damage models makes it possible to predict the residual load-bearing capacity, estimate the remaining service life, and optimize repair and strengthening strategies. The most widely used approaches for describing damage include: continuum damage mechanics (CDM), combined damage-plasticity models (such as Concrete Damage Plasticity, CDP), microplane models, accumulative fatigue damage models, as well as modern data-driven and machine-learning techniques for diagnostics and degradation prediction.

Each approach has its strengths and weaknesses in terms of reproducing crack initiation and propagation, capturing anisotropy of damage, representing reinforcement – concrete interaction, and ensuring numerical stability in finite element implementations. Therefore, these methods require a deeper analysis and the identification of the most appropriate areas of application. This article is aimed at highlighting such cases in the context of modern structural design and analysis of RC elements with damage.

## Materials and methods

As a result of the ongoing military actions in Ukraine, the number of damaged buildings and structures has increased dramatically (Surianinov, Neutov & Yesvandzhyia, 2023). The most reliable and straightforward method of reconstruction is to replace the most critically damaged structural elements with new ones. However, this approach is also the most expensive, which makes it economically inefficient under current conditions. Therefore, greater emphasis should be placed on the diagnostics and inspection of structures. Identifying the type of damage and its impact on the load-bearing capacity of structural elements is a pressing task (Blikharskyy & Kopiika, 2022), while establishing a more accurate stress-strain state (Barabash, Kostyra & Tomashevskyi, 2022) makes it possible to preserve parts of existing structures, strengthen them, or even extend their service life instead of replacing them immediately.

In this regard, the focus should be on the most common mathematical models of damage and the mechanics of their behavior, which have been developed and applied in both Ukrainian and international practice:

Theoretical Background of Damage Models

1. Continuum Damage Mechanics (CDM) (Voyiadjis, Shojaei, Li, & Kattan, 2012)

Continuum Damage Mechanics (CDM) represents one of the most fundamental approaches to modeling the degradation of concrete properties. Within this framework, a scalar or tensor damage variable is introduced, which directly affects the material's modulus of elasticity (Fig. 1). This indicator reflects the progressive accumulation of microcracks and the deterioration of the concrete structure under loading, ultimately leading to a reduction in stiffness. The classical works of J. Mazars (Mazars, 1984) and J. L. Chaboche (Chaboche, 1988) initiated the application of this approach to concrete, formulating a mathematical model of damage evolution as a function of strain.

A direct three-dimensional extension of the preceding uniaxial formulation is provided by the well-known Lemaitre – Chaboche (Lemaitre et al., 1978) 3D elastic damage model. In this approach, building on the fundamental principles outlined in Section 1, it is assumed that the stiffness tensor **D** of the damaged material is expressed as follows:

$$D = (1 - \omega)D_0, \tag{1}$$

where $\omega$ – damage variable; $D_0$ – denotes the elastic stiffness of the undamaged material.

The advantages of CDM include the simplicity of its formalization and the relative efficiency of implementation in numerical methods, particularly in finite element analysis. It enables the description of the transition from the elastic to the damaged state and effectively models the cracking stage. The schematic in Fig. 1 illustrates the damage and healing mechanism of a discontinuous fluid. Point A marks the beginning of unloading, where the material already contains plastic deformations and microdefects such as cracks and voids. Point B corresponds to the healing stage, from which reloading begins. After healing, the material demonstrates an increased elastic modulus.

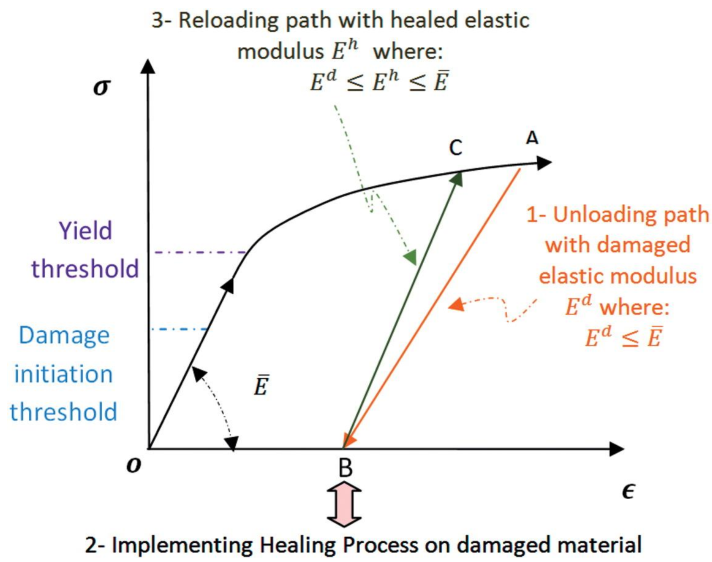


*Fig. 1. Basic idea of Continuum Damage Mechanics (CDM) (Voyiadjis et al., 2012)*

At the same time, continuum damage models have several significant limitations. The main challenge is strain localization in finite element calculations, which results in mesh dependence – the outcomes are influenced by the discretization size. This phenomenon leads to unrealistic strain concentrations and requires additional strategies, such as introducing non-local or gradient terms, to ensure objectivity of the results. Moreover, basic CDM formulations often fail to account for the differences between the behavior of concrete in compression and in tension, which restricts their accuracy under complex loading scenarios.

However, modern researchers are attempting to propose solutions that enable more efficient use of continuum damage models. For instance, in the study (Rezaei et al., 2022), numerical examples and specific features of finite element implementation are presented, where fracture energy and material strength are introduced as arbitrary functions dependent on the crack propagation direction. The application of the proposed anisotropic cohesive fracture model ensures convergence of the results with respect to the characteristic length-scale parameter by accounting not only for fracture energy but also for the direction-dependent material strength. This methodology allows for increasing the finite element mesh size, which significantly reduces computational time without substantially affecting the predicted crack path and the obtained load-displacement curves. Nevertheless, such models are still unable to fully capture fracture properties dependent on the stress state mode.

Despite these drawbacks, CDM remains the foundation for the development of more advanced approaches, including combined “damage – plasticity” models, and continues to serve as a conceptual basis for both engineering practice and scientific research.

2. Damage-Plasticity Models (Lee & Fenves, 1998)

Damage-plasticity models combine two fundamental concepts: plasticity mechanics and continuum damage mechanics. Plasticity represents the irreversible deformations of a material once the yield limit is exceeded, while the damage variable describes the progressive degradation of stiffness due to microcrack formation. One of the most well-known models of this class is the Lubliner – Oliver – Oller – Oñate model (Lubliner, Oliver, Oller & Onate, 1989), which laid the foundation for the development of more practical implementations. Later, Lee and Fenves (1998) (Lee & Fenves, 1994; Lee, 1996) extended this concept to cyclic loading, introducing separate damage variables for tension and compression. In modern numerical methods, the most common implementation is the Concrete Damage Plasticity (CDP) model, integrated into software packages such as ABAQUS, DIANA, and SOFiSTiK. It allows for the reproduction of complex concrete behavior, including the asymmetry between compression and tension, the accumulation of plastic strains, and the gradual reduction of stiffness.

Fig. 2 illustrates the combination of plasticity and damage models, where thick lines denote loading branches and thin lines denote unloading and reloading branches. Pure plasticity models (Fig. 2, *a*) are capable of reproducing characteristic deformations of concrete, but they fail to capture the progressive stiffness degradation of the structure (Al-Zuhairi, Al-Ahmed, Abdulhameed, & Hanoon, 2022). Conversely, pure damage models (Fig. 2, *b*) can correctly describe the process of stiffness deterioration but do not reproduce the real deformations observed in experiments. Therefore, as shown in Fig. 2, *c*, combining these two approaches is considered a necessary and effective tool for adequately describing the nonlinear behavior of concrete, providing a more comprehensive representation of its actual stress-strain state.

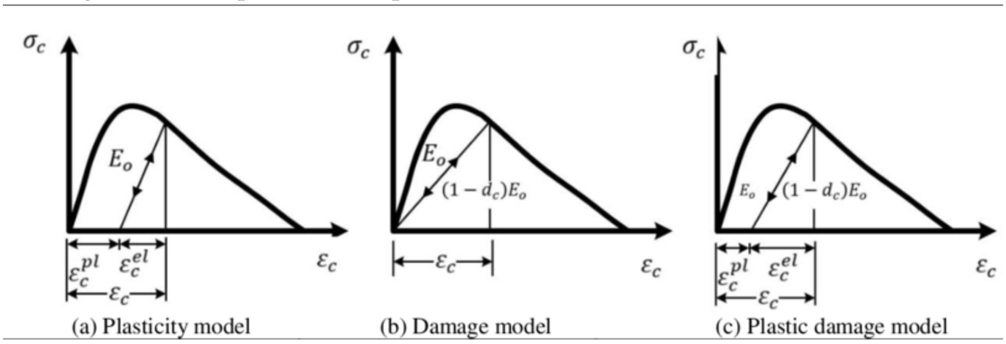


*Fig. 2. Representation of concrete damage plasticity (Al-Zuhairi et al., 2022)*

The basic stress-strain relation can be expressed as:

$$\sigma = (1-D)-C_0:(\varepsilon-\varepsilon^p), \quad (2)$$

where $\sigma$ – stress tensor; $D\in[0,1]$ – **damage variable** (0 for undamaged, 1 for fully damaged material); $C_0$ – elastic stiffness tensor of the undamaged material; $\varepsilon$ – total strain tensor; $\varepsilon^p$ – plastic strain tensor.

The term $(1-D)$ represents stiffness degradation, while $\varepsilon^p$ accounts for irreversible deformations.

Despite their high versatility, damage-plasticity models also have certain limitations. First, they are parameter-intensive: accurate performance requires careful identification of numerous material properties, many of which are often difficult to determine experimentally. Second, if parameters are improperly selected, the model may exhibit numerical instability, particularly in problems involving repeated loading or complex three-dimensional stress states. Nevertheless, this group of models is currently considered the most balanced for engineering practice, as it combines conceptual rigor with the ability to reproduce a wide range of loading scenarios. For this reason, damage-plasticity approaches are widely applied to the analysis of beams, slabs, columns, foundations, and other reinforced concrete elements under various operating conditions.

3. Microplane Models (Bažant et al.) (Caner & Bažant, 2013)

Microplane models represent one of the most accurate approaches to describing concrete damage at the microstructural level. Their foundation lies in the concept of representing the material through a set of planes with different orientations (microplanes), on which individual constitutive stress-strain laws are defined. This formulation makes it possible to capture anisotropy and complex crack formation mechanisms that cannot be adequately represented by classical isotropic models. Starting from models M1–M4, developed by Bažant and Caner in the 1990s (Caner & Bažant, 2000), the mathematical framework has been gradually refined, leading to more advanced versions such as M7. The latter accounts for the influence of triaxial stress states, cracking phenomena, and nonlinear behavior under both tension and compression.

The model applies the concept of kinematic constraints and stress homogenization to establish the relationship between the macroscopic and microplane levels of discretization (Baktheer, Aguilar & Chudoba, 2025), as illustrated in Fig. 3. Through this approach, the microplane formulation enables a more accurate description of material behavior, particularly in the presence of complex anisotropic damage. Microplane models recognize that each fixed orientation in the solid angle defines a microplane associated with its corresponding constitutive response.

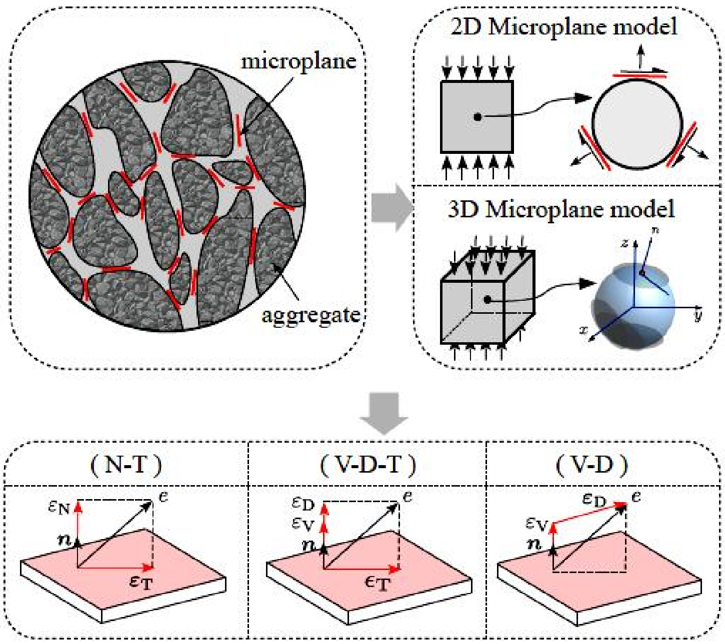


*Fig. 3. The concept of the microplane theory for constitutive modeling of quasi brittle materials (Baktheer et al, 2025)*

The kinematic constraint in microplane models for concrete is essential for accurately representing strain-softening behavior. This means that the microplane strains are defined as the projections of the overall strain tensor onto the individual microplanes.

In microplane models, the kinematic relationship establishes the link between the macroscopic strain tensor and the strain components acting on each microplane. The strains on a microplane, defined by its unit normal vector n are obtained by projecting the macroscopic strain tensor ε onto that plane.

The **normal strain** component is expressed as:

$$\varepsilon_N = n \cdot \varepsilon \cdot n \tag{3.1}$$

and the **tangential strain** component as:

$$\varepsilon_T = \varepsilon \cdot n - \varepsilon_N \cdot n \tag{3.2}$$

Here $\varepsilon_N$ – normal strain acting perpendicularly to the microplane; $\varepsilon_T$ – tangential strain vector acting within the plane; ε – macroscopic strain tensor; *n* – unit normal vector defining the orientation of the microplane.

The main advantage of microplane models is their ability to reproduce multidimensional effects and provide high accuracy in modeling three-dimensional structures, including slabs, shells, and complex joints. At the same time, they remain extremely demanding in terms of computational resources and require a large number of parameters for calibration (Nastri, Tenore & Todisco, 2023), which limits their widespread use in practical engineering. Most often, they are employed in scientific research aimed at verifying new experimental data or for benchmarking against more simplified models. In the future, the development of hybrid approaches that integrate microplane modeling concepts with machine learning techniques (Benelfellah et al., 2017) may pave the way for their more efficient implementation in engineering practice.

4. Fatigue / Accumulative Damage Models (Shiri et al., 2015) (Palmgren – Miner, extended cumulative models for concrete)

Fatigue and accumulative damage models are aimed at describing the degradation of reinforced concrete elements under repeated cyclic loading. They are based on the hypothesis of progressive accumulation of micro-damages, which over time lead to a reduction in stiffness and load-bearing capacity. The most common analogy is the Palmgren – Miner rule (Miner, 1945), which defines the cumulative effect of load cycles on the service life of a material. Within this approach, the stress-strain state of each cycle is translated into an incremental damage contribution, and failure occurs once the critical value of the damage variable is reached.

The stiffness degradation of a material due to accumulated damage is expressed by a modified Hooke's law:

$$\sigma = (1 - D)\, E_0\, \varepsilon, \tag{4}$$

where σ – actual stress; $E_0$ – initial elastic modulus; ε – strain; $D \in [0,1]$ – accumulated damage variable.

As *D* increases, the effective stiffness $(1-D)E_0$ decreases progressively.

Such models are widely applied in the assessment of durability for bridges, road slabs, floor structures, and other elements subjected to repeated loading. Fig. 4 illustrates the development of damage modeled using trigonometric expressions, which more accurately represent the nonlinear stiffness degradation of the material throughout the loading cycle. These functions provide improved life prediction compared to other methods that require numerous parameters and extensive experimental data.

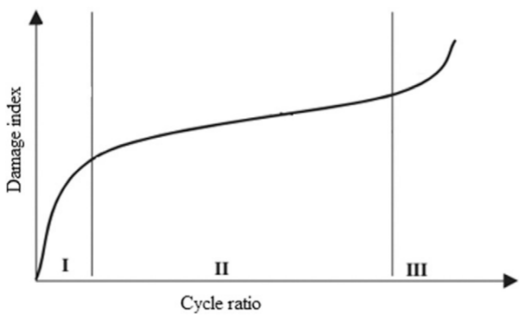


*Fig.4. Schematic of fatigue damage evolution in composites (Shiri et al, 2015)*

Nowadays, the continuum damage mechanics (CDM) approach is increasingly used for engineering calculations (Bobyr, Khalimon & Bondarets, 2013), since the main idea of such damage models lies in replacing the standard stress with an effective stress in the constitutive equation. Miner-type models have been further developed by modern researchers. In particular, in the study (Aeran, Siriwardane, Mikkelsen & Langen, 2017), a model was proposed that is formulated based on the general parameters of the material's *S–N* curve and does not require additional determination of material parameters or modification of the *S–N* curve. The comparison between experimental data and theoretical predictions confirmed the reliability of the fatigue damage modulus proposed by the authors.

The advantage of fatigue models is their practical orientation and the ability to predict long-term performance based on relatively simple parameters obtained from experimental *S–N* curves. At the same time, their main drawback is the empirical nature and limited applicability beyond the conditions under which they were calibrated. To enhance the reliability of predictions, modern research integrates micromechanical concepts, continuum damage theory, and machine learning methods into fatigue modeling. Such developments make it possible to combine the simplicity of classical empirical formulas with the flexibility and accuracy of advanced numerical analysis tools.

The presented table (Table) summarizes the key characteristics of the main groups of damage models for reinforced concrete structures. It systematizes four principal approaches: Continuum Damage Mechanics (CDM), damage-plasticity models (CDP), microplane models, and accumulative-fatigue approaches. For each group, the fundamental theoretical framework, fields of application, as well as the main advantages and limitations are outlined. Such a structured representation makes it possible to quickly identify in which cases the use of a particular approach is appropriate, as well as what potential challenges may arise during modeling.

**Comparison of Damage Models of Reinforced Concrete**

| Model | Principle | Parameters | Strengths | Weaknesses | Applications |
|---|---|---|---|---|---|
| Continuum Damage Mechanics (CDM) | Scalar / tensor damage vari-ables reduce stiffness due to microcrackin | Few (damage evolution laws) | Simple, efficient, captures stiffness degradation | Mesh dependence, requires regularization | Progressive cracking in beams, slabs |
| Damage-Plasticity (e. g., CDP in ABAQUS) | Combination of plasticity and damage (stiffness reduction) | Moderate (plastic + damage parameters) | Good for compression / tension asymmetry, cyclic loading | Parameter calibration difficult, sensitivity issues | Structural members under monotonic / cyclic loads |
| Microplane Models (e. g., M4, M7) | Constitutive laws applied on multiple oriented planes | Many (orientation-based parameters) | Captures anisotropy, 3D effects, crack orientation | Computationally expensive, parameter-rich | Complex 3D problems, fracture simulation |
| Fatigue / Accumulative Models | Damage accu-mulates per cycle (Palmgren – Miner type) | Empirical (fatigue constants) | Good for long-term cyclic loading, practical for bridges | Empirical, needs large experimental data | Bridges, slabs, long-term service life prediction |

The comparison shows that each group of models occupies a specific application niche. CDM offers simplicity of formalization and efficiency for general analysis, but it is vulnerable to the issue of mesh dependence. CDP models are the most suitable for engineering practice due to their ability to balance accuracy and computational complexity, although they require detailed parameter calibration. Microplane models ensure high accuracy and account for anisotropy, but they demand significant computational resources. Fatigue models are most useful for predicting durability under repeated loading, although they remain predominantly empirical. Thus, the table highlights that the choice of model depends on the purpose of analysis, ranging from fundamental research to practical engineering calculations.

## Results and discussions

The analysis of existing damage models for reinforced concrete structures has demonstrated their gradual evolution from phenomenological to advanced hybrid approaches. Continuum Damage Mechanics (CDM) models effectively reproduce the overall stiffness degradation but remain sensitive to mesh discretization parameters. Damage-plasticity (CDP) models have proven their practical value through integration into commercial software packages and their ability to balance accuracy with computational efficiency. Microplane models provide the highest accuracy in capturing anisotropic effects, yet they require substantial computational resources and detailed calibration. Fatigue models remain indispensable for predicting long-term durability under repeated loading, although their empirical nature limits universality.

The discussion of the comparison results highlights the absence of a universal approach suitable for all engineering tasks. The choice of model depends on the analysis objective: CDM is most appropriate for conceptual studies, CDP for engineering calculations in design practice, microplane approaches for high-precision scientific simulations, and fatigue models for long-term durability assessments. At the same time, a current trend in research is the integration of classical physico-mechanical models with machine learning tools, which reduces reliance on empirical assumptions and improves predictive capabilities under complex operating scenarios.

## Conclusions

The conducted review has confirmed the diversity of existing damage models for reinforced concrete structures while also identifying key challenges associated with their application. Each group of models has its unique advantages: CDM provides conceptual simplicity, CDP offers balanced accuracy and suitability for engineering calculations, microplane approaches enable detailed descriptions of three-dimensional material behavior, and fatigue models supply practical tools for long-term predictions. However, none of these approaches can fully meet all the needs of engineering practice, which emphasizes the necessity of developing combined and hybrid solutions.

A promising direction lies in the advancement of integrated models that combine physically based approaches with machine learning methods capable of processing large volumes of experimental and field data. Future research should be aimed at the standardization of calibration procedures, the creation of open experimental databases, and the development of multiphysics simulations. Such progress will improve the reliability of predictions, expand the applicability of damage models, and facilitate the implementation of new tools in modern engineering practice.

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## КЛАСИЧНІ МОДЕЛІ ПОШКОДЖЕНЬ ДЛЯ ЗАЛІЗОБЕТОНУ: ТЕОРІЯ, ЗАСТОСУВАННЯ ТА ОБМЕЖЕННЯ



У статті здійснено огляд моделей пошкодження залізобетонних конструкцій, які є ключовими для прогнозування їхньої міцності та довговічності. Під час експлуатації споруди зазнають дії багатофакторних навантажень, агресивного середовища й дефектів, що спричиняє мікротріщини, локальні пошкодження та втрату несучої здатності. Для описання цих процесів існує низка теоретичних і числових моделей, що відрізняються математичними підходами, практичними можливостями та обчислювальними витратами. У роботі систематизовано чотири основні групи: континуальна механіка пошкоджень (CDM), моделі пошкодження – пластичність (CDP), мікропланарні та накопичувально-втомні моделі.

CDM є базовим інструментом для описання деградації жорсткості на макрорівні, але обмежений локалізацією деформацій і залежністю від дискретизації. CDP поєднують пластичність і пошкодження, описуючи асиметрію поведінки бетону під час стискання і розтягу. Вони широко впроваджені у програмні комплекси і найзатребуваніші у проєктуванні. Мікропланарні моделі забезпечують найвищу точність відтворення анізотропних ефектів та складних тривимірних станів, але потребують значних ресурсів і великого обсягу експериментального калібрування, що обмежує їх використання у звичайних розрахунках. Втомні моделі залишаються незамінними для оцінювання довговічності під час дії циклічних навантажень, хоч ґрунтуються більше на емпіричних залежностях, що знижує їх універсальність.

Жодна із моделей не є універсальною. Вибір залежить від мети: для концептуальних оцінок – CDM, для проєктування – CDP, для високоточної симуляції – microplane, для прогнозування довговічності – втомні. Подальший розвиток пов'язаний із інтеграцією фізико-механічних підходів із цифровими технологіями, зокрема машинним навчанням і мультифізичними симуляціями, що забезпечить точність прогнозів і створення уніфікованих інструментів розрахунку.

**Ключові слова: моделі пошкоджень, залізобетонні конструкції, континуальна механіка пошкоджень, моделі пошкодження – пластичність, мікропланарні моделі, накопичувальні моделі пошкоджень.**