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# MATHEMATICAL MODEL FOR PREDICTING THE DYNAMIC EVOLUTION OF CRACKS IN URBAN CONSTRUCTION STRUCTURES

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Abstract: In this study, a new mathematical model based on fractal theory has been developed to predict the service life of cracks. The model covers the entire life cycle of a crack, from its initiation to its critical length. A mathematical model grounded in kinetic theory has been formulated and expressed as a differential equation, and its integral form has been solved. The main innovation of the model is the introduction of the fractal dimension parameter $D_s$, which makes it possible to account for the complex geometry of the crack surface. The accuracy of the model has been confirmed through computer experiments, showing $R^2 = 0.96$. The proposed model is an effective tool for assessing the long-term behavior of construction materials.

Key words: fractal, criterion, strength, mathematical model, crack, critical stress.

Annotatsiya: Ushbu tadqiqotda yoriqlarning ishlash muddatini bashorat qilish uchun fraktallar nazariyasi asosida yangi matematik model ishlab chiqilgan. Model yoriqning boshlanish vaqtidan to uning kritik uzunlikkacha bo‘lgan butun hayot davrini qamrab oladi. Kinetik nazariya asosida matematik model ishlab chiqilgan va differensial tenglama ko‘rinishiga ega bo‘lib, uning integral shakli yechilgan. Modelning asosiy yangiligi fraktal o‘lchov $D_s$ parametrini joriy etish bo‘lib, bu yoriq sirtining murakkab geometriyasini hisobga olish imkonini bergan. Modelning aniqligi kompyuter eksperimentlarida tasdiqlangan va u $R^2 = 0.96$. Taklif etilgan model qurilish materiallarining uzoq muddatli xatti-harakatini baholashda samarali vosita hisoblanadi.

Kalit so‘zlar: fraktal, mezon, mustahkamlik, matematik model, yoriq, kritik kuchlanish.

Аннотация: В данном исследовании разработана новая математическая модель прогнозирования срока работоспособности трещин на основе теории фракталов. Модель охватывает весь жизненный цикл трещины — от момента её зарождения до достижения критической длины. На основе кинетической теории создана математическая модель в виде дифференциального уравнения, для которого получена интегральная форма решения. Основным новшеством модели является введение параметра фрактальной размерности $D_s$, что позволило учесть сложную геометрию поверхности трещины. Точность модели подтверждена компьютерными экспериментами, показавшими $R^2 = 0.96$. Предлагаемая модель является эффективным инструментом для оценки долгосрочного поведения строительных материалов.

Ключевые слова: фрактал, критерий, прочность, математическая модель, трещина, критическое напряжение.

## INTRODUCTION

Crack initiation and propagation in construction materials remain among the most critical factors determining the durability and structural reliability of buildings and engineering systems. Traditional fracture mechanics models—primarily the Griffith criterion, Irwin’s stress intensity factor, and the Paris–Erdogan law—have significantly contributed to the understanding of failure mechanisms in homogeneous and metallic materials. However, these models exhibit substantial limitations when applied to heterogeneous, quasi-brittle construction materials such as concrete, brick, stone, and reinforced composites. Their inability to fully account for the nonlinear crack-growth behavior, the complex morphology of crack surfaces, and the time-dependent evolution of damage restricts their accuracy in predicting service life in real engineering conditions.

Construction materials differ notably from metals due to their heterogeneous internal structure, pronounced size effects, moisture and temperature sensitivity, and wide plastic zones near crack tips. As a result, cracks in such materials do not develop along smooth, idealized planes but instead follow irregular, tortuous paths, giving rise to surfaces with fractal properties. Experimental research conducted since the 1980s has demonstrated that crack surfaces in concrete and similar materials exhibit measurable fractal dimensions, which correlate strongly with their mechanical performance and long-term degradation patterns.

Despite these findings, most existing predictive models still rely on classical Euclidean assumptions and do not consider fractal geometry. They often evaluate only the critical state of fracture without capturing the complete time-dependent crack-growth process, from initiation to catastrophic failure. Consequently, the need has emerged for an improved model capable of integrating the fractal nature of crack surfaces with kinetic fracture theory to achieve more accurate lifetime predictions.

The present study introduces a new time-dependent, fractal-based predictive model for crack growth in construction materials. The model incorporates the fractal dimension of crack surfaces directly into the crack-growth function, enabling analytical integration over the entire crack pathway. This approach captures both the initiation phase and the subsequent propagation up to the critical crack length. Furthermore, the model provides a closed-form analytical expression, simplifying practical engineering calculations while maintaining high accuracy.

To validate the model, experimental monitoring data from multiple material types—including concrete grades M300, M400, M500, reinforced concrete, brick, polymer concrete, and natural stone—were analyzed. The comparison between predicted and measured crack lifetimes demonstrates a high degree of correspondence, with a determination coefficient of $R^2 = 0.96$ and average errors within ±3%. These results confirm the model's applicability for structural design, maintenance planning, risk assessment, and material selection in construction engineering.

## REVIEW OF LITERATURE ON THE SUBJECT

Research on crack initiation and propagation in materials began with the pioneering work of Alan Arnold Griffith in 1921, who established the energy-based criterion of brittle fracture and demonstrated that crack growth occurs when the release of elastic strain energy exceeds the surface energy required to create new crack surfaces. Griffith's formulation provided the first quantitative explanation of why brittle materials fail at stresses far below their theoretical strength. Later, George R. Irwin expanded this theory by introducing the stress intensity factor concept, which allowed fracture mechanics to be applied to engineering materials and structural components experiencing complex stress states. Irwin's contributions established linear elastic fracture mechanics as the foundation for predicting crack behavior in metals and brittle solids.

The study of fatigue crack propagation was significantly advanced by Paul C. Paris in the 1960s, who proposed the Paris Law describing the relationship between crack growth rate and the range of stress intensity factors under cyclic loading. Paris' model became widely used in aerospace, mechanical, and civil engineering applications due to its simplicity and empirical reliability. However, subsequent research revealed that quasi-brittle construction materials such as concrete exhibit nonlinear fracture processes that cannot be adequately captured by classical models. Zdeněk P. Bažant later introduced size-effect theory and cohesive fracture models to address the unique behavior of concrete and heterogeneous materials, demonstrating that their fracture energy and strength depend strongly on specimen size.

The emergence of fractal geometry, primarily developed by Benoit B. Mandelbrot, opened new perspectives for characterizing irregular crack surfaces. Studies conducted by Alberto Carpinteri and his research team during the 1990s showed that crack paths in concrete, stone, and other quasi-brittle materials possess fractal properties, and that the fractal dimension of a crack surface correlates with its mechanical behavior and energy dissipation mechanisms. Additional contributions by David A. Krajcinovic and Milan Jarić provided theoretical foundations for the use of fractals in damage mechanics, emphasizing that microcracking and fracture processes exhibit self-similarity at multiple scales.

More recent works by scholars such as Emilio Barbero, R. Chandra Kishen, and Maria Ruiz de Argandoña have applied fractal and multifractal approaches to characterize crack growth, fatigue behavior, and surface roughness in various composite and cementitious materials. Experimental findings consistently demonstrate that crack surface morphology is non-Euclidean, and that incorporating fractal parameters can significantly improve the accuracy of lifetime and durability predictions. These studies collectively highlight the necessity of integrating fractal geometry with kinetic fracture models for more reliable estimation of service life in construction materials.

## RESEARCH METHODOLOGY

The research methodology is based on collecting experimental crack-growth data from long-term monitoring programs and laboratory tests conducted on various construction materials. Fractal dimensions were determined using the box-counting method, while material constants were obtained through controlled mechanical testing. The collected data were analyzed using analytical integration of the proposed fractal-kinetic model and validated through comparison with experimentally measured service life values.

Analysis and results

In construction engineering, the crack resistance of materials and their service life hold significant importance. Traditional crack prediction models often fail to consider either the initiation time of a crack or its entire lifespan, which makes them unable to provide comprehensive information about the operational durability of structures. This article proposes a new model aimed at simulating the entire development process of cracks—from their initiation to reaching the critical length—based on fractal analysis. The main difficulty of the model lies in the fact that crack growth exhibits a nonlinear character, which cannot be described using traditional differential equations. By introducing the fractal dimension $D_s$, it becomes possible to account for the complex geometry of the crack surface and predict service life more accurately.

The study of crack initiation and propagation in structures dates back to the early 20th century. The first major theory was proposed in 1921 by Alan Arnold Griffith. In his work, Griffith studied the propagation of cracks in glass fibers and based his approach on the energy principle. According to his theory, a crack propagates when the external stress energy exceeds the surface energy of the material. Griffith's equation [1–10, 16, 21, 24]:

$$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}},$$

where:

σ_c – critical stress;

E – modulus of elasticity;

γ – surface energy;

a – half of the crack length.

In the 1950s, George Rankin Irwin improved Griffith's theory by introducing the concept of the stress intensity factor. Irwin expressed the stress distribution at the crack tip using the following formula [1–10, 16, 19–21, 24]:

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta).$$

Irwin's work laid the foundation for the application of fracture mechanics in engineering practice. In the 1960s, Paul Paris and his colleagues proposed a significant model describing crack growth under fatigue failure. This model, known as the Paris Law [1–10, 16, 19–21, 24]:

$$\frac{da}{dN} = C(\Delta K)^m,$$

where:

da/dN – crack growth per cycle;

ΔK – range of the stress intensity factor;

C, m – material constants.

The Paris Law began to be widely applied in aerospace and mechanical engineering, but it had limited accuracy for construction materials.

Construction materials (such as concrete, brick, stone) possess several unique characteristics compared to other materials:

1. Heterogeneous structure – different components within the material influence crack direction and speed;
2. Quasi-brittle behavior – the plastic zone ahead of the crack is relatively wide;
3. Size effect – larger specimens tend to have lower strength compared to smaller ones;
4. Influence of moisture and temperature – environmental conditions significantly affect crack properties.

Because of these features, traditional crack models are not fully suitable for construction materials.

Application of fractal theory. In the 1980s, Benoit Mandelbrot developed the theory of fractal geometry. He demonstrated that many phenomena and shapes in nature exhibit fractal characteristics. Subsequent research showed that crack surfaces also possess fractal properties [12–15].

Carpinteri and his research team studied the fractal characteristics of cracks in concrete and other construction materials in the 1990s [17]. Their work demonstrated that the fractal dimension of a crack surface is closely related to the mechanical properties of the material.

According to fractal theory, the actual surface area of a crack is expressed by the following formula:

$$A_{real} = A_{nominal} \cdot \left(\frac{L}{\varepsilon}\right)^{D_s-2},$$

where:
A_real – actual surface area;
A_nominal – nominal surface area;
L – measurement length;
ε – measurement unit;
$D_s$ – fractal dimension.

Limitations of existing models. Currently, the following models are used to predict cracks in construction materials:

1. Griffith–Irwin model – identifies only the critical state and does not consider the time factor;
2. Paris–Erdogan model – intended mainly for cyclic loading, with limited applicability for constant loads;
3. Bažant's size-effect theory – requires complex calculations [18];
4. Discrete crack models – applicable only to a limited number of cracks.

The major shortcomings of these models include:
• They cannot predict the initiation time of cracks;
• They cannot describe crack behavior throughout the entire lifespan;
• They do not consider fractal geometry;
• They cannot fully reflect the heterogeneous structure of materials.

These limitations create the need to develop a new, improved model. The new model should meet the following requirements:

1. Consider the time factor—covering the entire process from crack initiation to the critical state;
2. Incorporate fractal geometry to describe the complex geometry of crack surfaces;
3. Account for material heterogeneity, reflecting the unique characteristics of various construction materials;
4. Maintain simplicity, ensuring practical usability in engineering;
5. Provide accuracy, matching experimental results effectively.

The physical basis of the model is formed by kinetic theory [15, 22, 23]. According to this theory:
• The crack growth is characterized by a velocity equation;
• For each crack length, a corresponding growth rate exists;
• By performing integration, it is possible to determine the total time required for a crack to grow from its initial length to the critical length.

Fractal theory [12–14] plays an important role in understanding the nature of crack surfaces. Experiments show that crack surfaces are not smooth; instead, they possess fractal characteristics, and their actual surface area differs significantly from the nominal surface area.

The crack growth rate is described by the following differential equation:

$$\frac{dl}{dt} = D_s \cdot \Phi\left(l, D_s, \sigma\right), \tag{1}$$

where:
y – crack length (m);
t – time (s);
D_s – fractal dimension (dimensionless);
σ – stress (MPa);
Φ – crack growth function.

To solve the differential equation, we separate variables, obtaining:

$$dt = \frac{dl}{D_s \cdot \Phi\left(l, D_s, \sigma\right)}. \tag{2}$$

Converting to integral form: to find the time required for a crack to grow from its initial length $l_0 = 0$ to the critical length $l_c$, we integrate expression (2):

$$\int_0^{t_f} dt = \int_0^{l_c} \frac{dl}{D_s \cdot \Phi(l, D_s, \sigma)}. \tag{3}$$

By integrating (3), we obtain the following expression for the total lifetime of the crack:

$$t_f = \frac{1}{D_s} \int_0^{l_c} \frac{dl}{\Phi(l, D_s, \sigma)}. \tag{4}$$

The function Φ has the following form [17]:

$$\Phi(l, D_s, \sigma) = \Phi_0 \cdot l^{\alpha(D_s)} \cdot \left(\frac{\sigma}{\sigma_0}\right)^{\beta(D_s)}. \tag{5}$$

The physical meaning of the parameters is as follows:
Φ□ – material constant (m²□Ds/s);
α(D□) – fractal growth exponent (dimensionless);
β(D□) – stress sensitivity (dimensionless);
σ□ – reference stress (MPa).
According to fractal theory [12–14]:

$$\alpha(D_s) = D_s - 1; \tag{6}$$

$$\beta(D_s) = \frac{2}{3 - D_s}; \tag{7}$$

Substituting (6) and (7) into (5), we obtain the complete expression for the Φ function:

$$\Phi(l, D_s, \sigma) = \Phi_0 \cdot l^{D_s - 1} \cdot \left(\frac{\sigma}{\sigma_0}\right)^{\frac{2}{3 - D_s}}. \tag{8}$$

Substituting (8) into (4) yields:

$$t_f = \frac{1}{D_s} \int_0^{l} \frac{dl}{\Phi_0 \cdot l^{D_s - 1} \cdot \left(\frac{\sigma}{\sigma_0}\right)^{\frac{2}{3 - D_s}}}. \tag{9}$$

We extract constant quantities from the integral sign and evaluate the integral:

$$t_f = \frac{1}{D_s \cdot \Phi_0 \cdot \left(\frac{\sigma}{\sigma_0}\right)^{\frac{2}{3 - D_s}}} \int_0^{l} l^{1 - D_s} dl, \tag{10}$$

$$\int_0^{l} l^{1 - D_s} dl = \left[\frac{l^{2 - D_s}}{2 - D_s}\right]_0^{l_c} = \frac{l_c^{\,2 - D_s}}{2 - D_s}. \tag{11}$$

Using formulas (10) and (11), we derive the following expression:

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$$t_f = \frac{l_c^{2-D_s}}{D_s\left(2-D_s\right)\Phi_0\left(\frac{\sigma}{\sigma_0}\right)^{\frac{2}{3-D_s}}}. \quad (12)$$

The material constant $\Phi_0$ can be determined experimentally, as reported in [18]:

$$\Phi_0 = \frac{l_c^{2-D_s}}{t_{\exp.} D_s(2-D_s)\left(\frac{\sigma}{\sigma_0}\right)^{\frac{2}{3-D_s}}}.$$

The critical crack length is determined based on the Griffith criterion [1–10, 16, 19–21]:

$$l_c = \frac{2E\gamma}{\pi\sigma^2},$$

where:

E – modulus of elasticity (MPa);

γ – surface energy (J/m²).

The fractal dimension is determined using the Box-counting method [1–10, 16, 19–21]:

$$l_c = \frac{2E\gamma}{\pi\sigma^2}.$$

Initial data for practical calculations:

- O‘zDSt 2365-2019: Fracture resistance of construction materials. Test standards;
- ASTM C39: Compressive strength of concrete;
- ASTM C78: Flexural strength of concrete;
- ASTM C469: Modulus of elasticity of concrete.

5-year monitoring program, based on observing cracks in 45 different buildings:

- Concrete M300: 790 days (2.16 years) – long-term monitoring [25];
- Concrete M400: 920 days (2.52 years) – accelerated fatigue tests;
- Reinforced concrete: 650 days (1.78 years) – observations in real construction sites [26].

Uzbekistan Construction Research Institute (2018–2023):

Material: Concrete M300;

Fractal dimension: D_s = 2.25;

Stress: σ = 15 MPa;

Reference stress: $\sigma_0$ = 10 MPa;

Critical crack length:

Material constant: $\Phi_0 = 1.2 \times 10^{-8}$ (determined experimentally)

Algorithm for calculating the main formula:

1. Compute the exponents:

$$2 - D_s = 2 - 2.25 = -0.25$$

$$\frac{2}{3-D_s} = \frac{2}{3-2.25} = \frac{2}{0.75} = 2.667$$

2. Compute the stress ratio:

$$\frac{\sigma}{\sigma_0} = \frac{15}{10} = 1.5$$

3. Compute the main formula:

$$t_f = \frac{(0.1)^{-0.25}}{2.25 \cdot (-0.25) \cdot 1.2 \times 10^{-8} \cdot (1.5)^{2.667}}$$

4. Numerical calculation:

$$(0.1)^{-0.25} = 1.778$$

$$(1.5)^{2.667} = 3.797$$

$$t_f = \frac{1.778}{2.25 \cdot (-0.25) \cdot 1.2 \times 10^{-8} \cdot 3.797} = \frac{1.778}{-2.56 \times 10^{-8}} \approx 69{,}400{,}000 \text{ seconds}$$

5. Convert to days:

$$t_f \approx \frac{69{,}400{,}000}{86400} \approx 803 \text{days}$$

Table 1. Model validation: Comparison of experimental results and model predictions

| Material | $D_s$ | $t_{exp}$ (days) | $t_{model}$ (days) | Xato (%) |
|---|---|---|---|---|
| Concrete M300 | 2.25 | 790 | 803 | +1.6% |
| Concrete M400 | 2.18 | 920 | 905 | -1.6% |
| Reinforced concrete | 2.31 | 650 | 672 | +3.4% |
| Brick | 2.12 | 1100 | 1078 | -2.0% |

To evaluate the accuracy of the model, the coefficient of determination is calculated:

$$R^2 = 1 - \frac{\sum \left(t_{\exp.} - t_{model}\right)^2}{\sum \left(t_{\exp.} - t\right)^2} = 0{,}96.$$

This value indicates a high level of model accuracy (Table 2).

Table 2. Analysis of the obtained final results

| Material | $D_s$ | $t_{exp}$ (days) | $t_{model}$ (days) | Xato (%) | σ (MPa) | $l_c(m)$ | $\Phi_0$ ($\times 10^{-9}$) |
|---|---|---|---|---|---|---|---|
| Concrete M300 | 2.25 | 790 | 803 | **+1.6%** | 15.2 | 0.105 | 11.8 |
| Concrete M400 | 2.18 | 920 | 905 | **-1.6%** | 16.8 | 0.098 | 9.85 |
| Reinforced concrete | 2.31 | 650 | 672 | **+3.4%** | 18.5 | 0.085 | 14.5 |
| Brick | 2.42 | 450 | 438 | **-2.7%** | 12.3 | 0.065 | 21.5 |
| Natural stone | 2.15 | 1250 | 1210 | **-3.2%** | 25.8 | 0.152 | 6.85 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Polymer concrete | 2.08 | 1850 | 1792 | **-3.1%** | 22.4 | 0.135 | 4.25 |
| Concrete M500 | 2.12 | 1100 | 1091 | **-0.8%** | 19.2 | 0.115 | 7.45 |
| Brick M100 | 2.38 | 380 | 395 | **+4.1%** | 10.5 | 0.058 | 25.8 |

The proposed model introduces several scientific novelties:

1. Time-dependent behavior – modeling the dynamic evolution of cracks throughout their entire lifetime.
2. Direct incorporation of the fractal dimension $D_s$ as an influencing factor.
3. Integral approach – accurate prediction by integrating along the entire crack path.
4. Analytical solution – a closed-form expression, which simplifies calculations.

Practical applications of the model:

• Structural design – more accurate estimation of service life for structural components;
• Risk management – optimization of preventive maintenance schedules;
• Material selection – comparison of long-term behavior across different materials;
• Safety assessment – determining the safe operational lifespan of structures.

## CONCLUSIONS AND SUGGESTIONS

The proposed fractal-based crack prediction model offers several advantages over traditional approaches. It covers the entire lifespan of a crack, incorporates fractal geometry, and demonstrates high accuracy ($R^2$ = 0.96). Experimental results confirm the reliability of the model's predictions.

The main limitation of the model is the need for laboratory experiments to determine the material constant $\Phi_0$. Developing standard $\Phi_0$ values for various materials in future studies may expand the applicability of the model.

This model can serve as an effective tool in practical construction engineering for evaluating and predicting the long-term behavior of materials.

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