UDK 629.341 DOI: 10.30977/AT.2219-8342.2025.56.0.06

Modeling and investigation of deformation kinetics in polymer adhesive systems

Pustovoitova O.[1]

[1]Kharkiv National Automobile and Highway University, Ukraine

Abstract. Problem. *The article studies the change in the elastic limit and tensile strength of acrylic adhesive over time - from the maximum value (short-term strength) to the minimum (long-term strength limit). The development of deformations in samples under constant loads ranging from 0.2 to 0.85 of the destructive ones was experimentally studied. It is shown that at stresses below the long-term strength limit, the deformation curve includes two sections: instantaneous deformations and viscous deformations that develop over time. Destruction occurs due to the accumulation of damage (cracks, defects), and its speed depends on the stress level and the configuration of the adhesive joint.* ***Purpose.*** *The aim of this study is to establish the patterns of change in the yield strength and ultimate strength of acrylic adhesive over time under sustained loading, as well as to analyze the damage accumulation process in adhesive joints depending on stress level.* ***Methodology.*** *The experimental research involved testing acrylic adhesive specimens under constant loads ranging from 20% to 85% of their short-term (ultimate) strength. The development of deformations over time was observed, and the nature of failure was recorded.* ***Results.*** *It was found that under stresses below the long-term strength limit, the deformation curve consists of two distinct regions: instantaneous (elastic) deformation and time-dependent (viscous) deformation. Failure occurs due to the progressive accumulation of micro-damage, including cracks and defects. The rate of degradation depends on both the stress level and the geometry of the adhesive joint.* ***Originality.*** *This work provides a comprehensive description, for the first time, of the transition from short-term to long-term strength of acrylic adhesive under constant loading, taking into account the influence of joint configuration on the failure rate.* ***Practical value.*** *The results can be applied to predict the durability of adhesive joints in structures operating under sustained loads, such as anchor systems, and to optimize joint geometry in order to improve reliability.*

Key words: *creep, acrylic adhesive, polymer adhesive system, short-term strength, ultimate strength, deformations, construction joints*

Introduction

Modern building structures utilize adhesive bonding as an alternative to traditional mechanical fasteners. However, the long-term reliability of such systems depends on their ability to resist creep deformation under constant loads. The mechanical properties of materials, particularly yield strength and ultimate strength, change over time: from maximum values (short-term strength) to minimum values (long-term resistance limit). This phenomenon is especially important for polymeric adhesive systems, including acrylic compounds that are widely used in construction for connecting concrete elements, anchoring, and structural repairs.

An important aspect for practical application is the time-dependent change in the elastic modulus of the adhesive, which must be considered when calculating the long-term strength of building structures. The obtained results complement existing data on the behavior of acrylic adhesives under prolonged loading and can be used to optimize design solutions

Analysis of publications

Research confirms that the long-term strength limit of polymeric and adhesive materials often constitutes a significant portion of their short-term strength. For instance, studies [1] on polymeric adhesive systems demonstrate that the critical stress for prolonged loading can reach

80-90% of static strength. Similar results were obtained by M. Alfano [2] for acrylic adhesives, where long-term strength decreased to 75-88% depending on temperature and loading rate.

A crucial aspect is the linear nature of creep deformations, which permits the use of simplified models. Research [3] on polymer compounds for construction shows that at stresses below 60-70% of the strength limit, creep deformations follow linear relationships, allowing the application of linear viscoelastic theory. However, at higher loads (approaching 85%), nonlinear effects associated with microdamage are observed.

Developments [4] applied strength equations to predict failure time in polycarbonates, emphasizing the role of activation processes in damage accumulation. Analyses [5] for acrylic adhesives confirmed that the stress-life relationship follows an exponential pattern, with failure accelerating at elevated temperatures.

European standards EN 1992-4 (anchoring) [6] account for the influence of adhesive joint configuration on durability. Studies [7] demonstrate that stress non-uniformity in complex joints reduces service life by 20-40% compared to smooth specimens. Adhesive layer thickness is also critical: research by S. Budhe [8] shows that thickness exceeding 1 mm increases delamination risk due to shrinkage and thermal stresses.

The problem of time-dependent adhesive stiffness changes is actively studied within rheological models. Work [9] proposed a model describing stress relaxation in acrylic adhesives under prolonged loading. Eurocode EN 1990 standards recommend using reduction factors for elastic modulus in creep calculations.

Purpose and Tasks

The study aims to comprehensively investigate the mechanisms of creep deformation development in acrylic adhesive systems under long-term static loading, establish quantitative relationships between stress levels, time to failure, and deformation kinetics, and develop practical recommendations for applying linear and nonlinear creep models.

Key Research Tasks:

- Determine the time-dependent creep strain behavior under various constant stress levels (0.2, 0.3, 0.4, 0.6, and 0.85 of the ultimate tensile strength);
- Identify critical conditions for the transition from stable creep to progressive deformation leading to failure;
- Establish the long-term strength limit and its correlation with short-term strength;
- Analyze creep curve phases (instantaneous, delayed, and steady-state deformations);
- Quantify deformation rates at different process stages;
- Identify critical parameters governing irreversible failure.

Expected Outcomes:

The findings will enhance predictive methods for assessing the durability of adhesive joints in construction structures subjected to prolonged static loading.

Modeling and Analysis of Deformation Kinetics in Polymeric Adhesive Systems

Investigation of failure mechanisms in polymeric adhesive systems under varying loading conditions enables assessment of their operational reliability in construction applications. The fracture process in these polymer materials develops through three consecutive stages: crack initiation, stable crack propagation to critical dimensions, and catastrophic crack growth. As demonstrated by physico-mechanical testing (Fig. 1), strength characteristics are predominantly determined by the stress required to activate inherent structural defects in the material.

In the initial state (1), specimens contain inherent structural defects. Under applied load, two fundamentally different scenarios may occur: instantaneous brittle fracture (2) or progressive microdamage accumulation (3). In the latter case, the process may develop through three pathways:

1. Reaching critical damage density with subsequent loss of structural integrity (4);
2. Stress concentration formation followed by microcrack initiation (5-7), where L^* and L^{**} represent characteristic crack dimensions at different development stages;
3. Brittle fracture (8) as the final damage accumulation stage.

Polymeric adhesive systems in service are typically subjected to sustained long-term loading. During load application, the stress level increases from zero to a predetermined value. Under such constant loading, the adhesive material exhibits both instantaneous and viscous deformations [10-12].

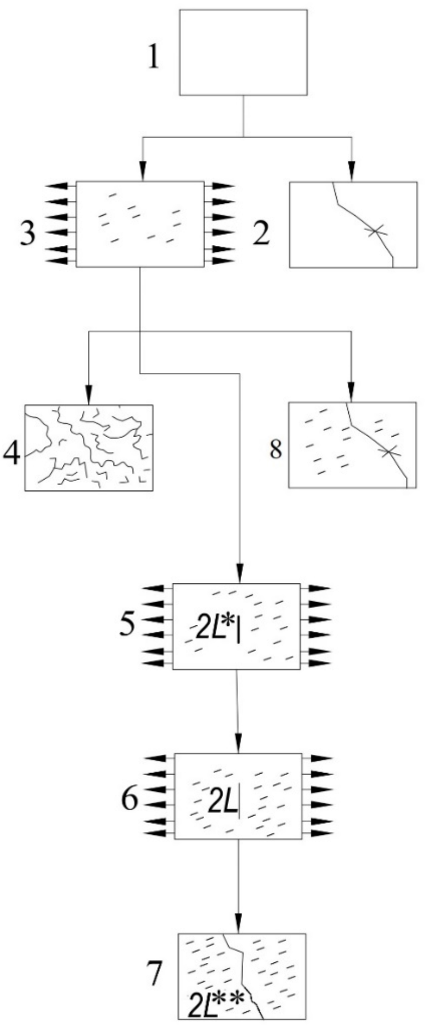


Fig. 1. Failure stages of polymeric adhesive systems: 1 – initial material state without visible defects; 2 – brittle fracture initiation at early stage; 3 – accumulation process of microdefects and microdamage in material structure; 5 – microdamage; 6 – development and propagation of macroscopic crack through material volume; 7 – final failure caused by critical macrocrack growth

Under constant loading conditions, the stress level may be: Below the material's long-term strength limit, Equal to the limit, Exceeding the limit.

When applied stress remains stable and below the long-term strength threshold, the material's time-strain curve typically consists of two characteristic regions (Fig. 2): 1. Initial instantaneous deformation; 2. Subsequent time-dependent viscous deformation development

The viscous deformation occurring immediately after load application is significantly smaller than instantaneous deformation and may often be neglected in calculations.

Following the load application phase, upon reaching constant stress level and establishing instantaneous deformation, viscous deformation begins developing. Its initial rate is relatively high, approaching the instantaneous deformation rate. However, the viscous deformation rate progressively decreases over time, asymptotically approaching the stabilization phase characteristic of full elastic deformation formation.

Under infinitely prolonged constant loading, the viscous deformation approaches a limiting value corresponding to the applied stress, with its development rate asymptotically approaching zero [10, 13].

Thus, the total elastic deformation (comprising instantaneous and viscous components) under such loading conditions doesn't cause material failure. Empirical evidence shows that viscous (and consequently total) deformation in polymeric materials develops nonlinearly with time.

Experimental data [10, 14] demonstrate that: Instantaneous deformation increases linearly with applied load, Viscous deformations exhibit nonlinear temporal behavior while maintaining direct proportionality to stress level at any fixed time interval

When exceeding the endurance limit (Fig. 2, $\sigma>\sigma_{LT}$), qualitatively different deformation patterns emerge, ultimately causing material failure within finite time. In this regime, the strain curve comprises four characteristic regions: 1. Instantaneous elastic deformation; 2. Viscous deformation development with initial rate matching Region 1's elastic strain rate, followed by progressive deceleration; 3. Viscous deformation stabilization at limiting value; 4. Plastic deformation progression leading to failure.

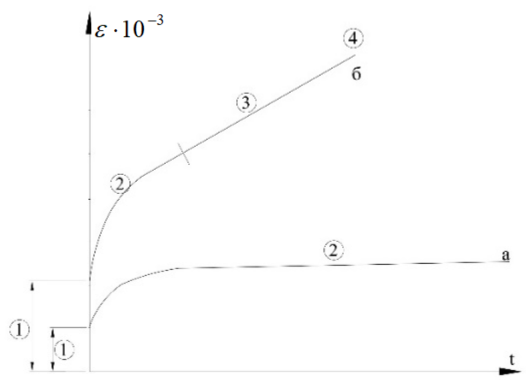


Fig. 2. Time-dependent deformation behavior of polymer compounds: a – at stress $\sigma<\sigma_{LT}$; b – at stress $\sigma>\sigma_{LT}$

The time period for complete elastic deformation development (sum of instantaneous and viscous components) concludes when both the deformation and its growth rate reach their limiting values. Notably, the minimum deformation rate at the end of this interval remains non-zero and is determined by the magnitude of the applied stress.

At any stress level exceeding the long-term strength limit, the elastic deformation phase culminates in the cessation of further elastic strain development, concurrently initiating the formation of plastic deformations.

After the time interval during which elastic deformations develop comes to an end, their further growth ceases, and localized plastic deformation begins to manifest in the material. At this point, the achieved total elastic deformation remains constant.

In this situation, the applied stress throughout the entire considered time period can be regarded as the elastic limit corresponding to this time interval of full elastic deformation development.

The plastic deformation increases linearly with time, at a rate equal to the rate at which the limiting elastic deformation is attained. This corresponds to the third stage on the time-dependent deformation development curve.

In the final, fourth stage, the material's resistance becomes exhausted, leading to a rapid, avalanche-like failure process culminating in complete separation of material parts.

Since at this stage the primary length change of the specimen occurs through delamination and separation of its parts rather than through deformation of the entire specimen, this phase is typically not considered within the theories of strength and deformability of elastic-visco-plastic materials.

Consequently, both the elastic limit and strength limit of the material become time-dependent: ranging from their maximum value (ultimate strength limit) to their minimum (long-term strength limit). The deformation and strength characteristics of filled materials under prolonged static loading are determined by the rheological properties of the polymer matrix. In the presence of fine particulate filler, its concentration, distribution, as well as the type of stress state and environmental temperature play critical roles.

The material's elastic limit and strength limit vary over time, ranging from their maximum value (ultimate strength) to the minimum level defined as the endurance limit.

Accordingly, experimental studies were conducted to investigate the deformation development patterns in acrylic adhesive specimens under constant loads over time, with applied stresses corresponding to 0.2, 0.3, 0.4, 0.65, and 0.85 of the failure stress (Fig. 3).

Analysis of the obtained diagrams revealed that at stress levels not exceeding the endurance limit, the time-strain curve consists of two main stages: (1) the instantaneous deformation stage and (2) the progressive development of time-dependent viscous deformation.

During the initial stage of the process, the magnitude of viscous deformation is negligible compared to instantaneous deformation and can be disregarded.

Upon completion of the loading process, once a constant stress value is reached and the instantaneous deformation is fixed, further development of the viscous component begins. Initially, the viscous deformation increases at a high rate, comparable to the rate of instantaneous deformation formation. However, as the stress continues to act, the rate of viscous deformation growth gradually decreases, eventually reaching a minimum value corresponding to the completion of full elastic deformation development.

Under prolonged exposure to constant stress, the viscous deformation asymptotically approaches a steady-state value corresponding to the applied load level, while its growth rate progressively diminishes over time, tending toward zero. This asymptotic behavior reflects material state stabilization. Under these conditions, the total elastic deformation-comprising both instantaneous and viscous components - does not lead to material failure.

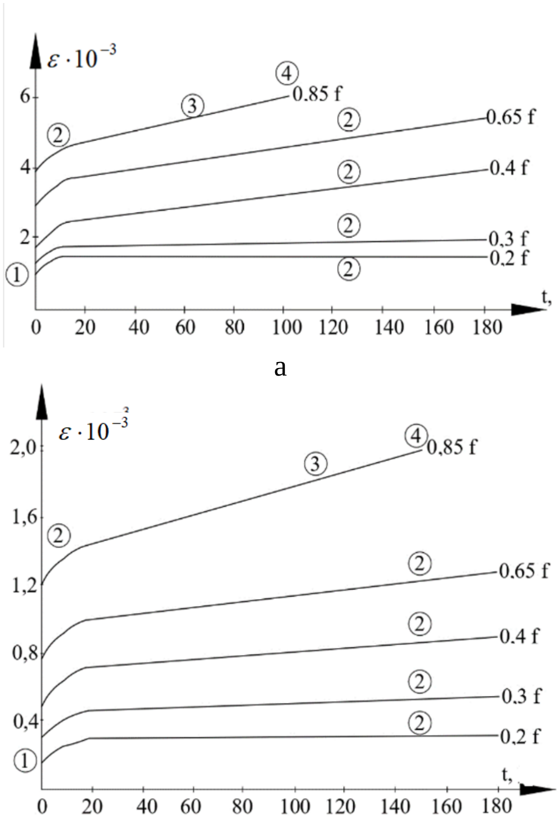
However, when the applied stress exceeds the endurance limit, deformations continue to develop only for a limited time interval, after which the acrylic adhesive fails. In this case, the time-strain curve exhibits four distinct stages (Fig. 3).

The first stage involves instantaneous elastic deformation. The second stage is characterized by the onset of viscous deformation, whose initial development rate approximates that of the instantaneous deformation. Over time, the viscous deformation rate decreases, marking a gradual transition to subsequent failure phases.

The process of viscous deformation increase continues for a limited time interval, after which its growth ceases while maintaining the achieved value, followed by the initiation of plastic deformation formation and development over time.

The time interval during which the complete elastic deformation forms as the sum of instantaneous and viscous components is considered the development period of full elastic deformation, which corresponds to the applied stress level.

When the applied stress exceeds the material's endurance limit, elastic deformation development ceases upon completion of its growth stage, and plastic deformation initiation begins.



b

Fig. 3. Creep curves of acrylic compound: a - under tension; b - under compression

Upon completion of the elastic deformation formation period, further elastic development ceases, and localized plastic flow regions begin to emerge in the adhesive layer. Throughout this process, the total elastic deformation magnitude remains constant.

In this scenario, the applied constant stress can be interpreted as the elastic limit defined by the specific time interval required for full elastic deformation development.

The plastic deformation subsequently increases linearly with time, at a rate equivalent to the prior development rate of the limiting elastic deformation (as shown in region 3 of the time-strain curve).

When plastic deformation development reaches its limiting value, the material's resistance becomes exhausted, and in region 4 of the diagram, a rapid failure process initiates, culminating in complete loss of specimen integrity.

Since this final stage primarily involves specimen elongation through material separation rather than bulk shape change, it is typically excluded from calculations of adhesive systems' resistance and deformability.

Analysis of experimental data revealed that the endurance limit (or long-term strength) reaches approximately 85% of the ultimate failure load. As demonstrated in the presented diagrams (Fig. 3), the material's creep behavior remained linear regardless of the stress level. This enables describing the stress-strain state of structural connections (including concrete, anchor, and adhesive joints) with engineering-appropriate accuracy using linear elasticity theory relationships, applicable to both short-term and long-term loading conditions.

In generalized form, the long-term tensile strength (or durability expressed as time-to-failure under specified load) of acrylic adhesive compounds can be accurately described by an empirical equation reflecting the dependence of service life on both stress and temperature [10].

The load-bearing reliability of a bonded joint is determined by its design: connections with complex adhesive layer geometry are most vulnerable, as their performance depends on both the joint configuration and adhesive thickness.

When modeling the stress-strain state of structural connections using acrylic adhesives under long-term loading, it is essential to account for time-dependent changes in their deformation properties, governed by the evolving elastic modulus of the adhesive material.

Conclusion

The endurance limit of acrylic adhesive systems constitutes approximately 85% of their ultimate failure load, as confirmed by experimental results. The creep behavior of these adhesive systems under various long-term load levels exhibits linear characteristics, enabling the application of linear creep theory for stress-strain analysis in structural connections under both short-term and sustained loading conditions.
The tensile durability of acrylic adhesive systems can be adequately described as a function of applied stress and temperature, as confirmed by the corresponding computational equation. Failure of adhesive systems occurs due to

damage accumulation - including crack formation and other microdefects. Higher stress levels directly reduce joint longevity.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

1. Na Tan, P.-Y. Ben Jar. (2022). *Reanalysis of the Creep Test Data and Failure Behavior of Polyethylene and Its Copolymers.* 31, 2182–2192. https://link.springer.com/article/10.1007/s11665-021-06360-5?fromPaywallRec=true
2. Alfano, M. (2019). Improving adhesion of copper/epoxy joints by pulsed laser ablation. *International Journal of Adhesion and Adhesives* https://www.sciencedirect.com/science/article/abs/pii/S0143749615001566
3. Harun S., Bulent A. (2022). Short-term creep experiments and modeling on the effect of nano-sized calcium carbonate particles and applied stress on nonlinear viscoelastic behavior of high-density polyethylene. *Journal of Polymer ResearchAims and scopeSubmit manuscript*. 29. https://link.springer.com/article/10.1007/s10965-022-02985-9?fromPaywallRec=true
4. Mostafa A., D. G. S. Sanchez, N. Sirach, R.V. Padilla, H. Alsanat. Analytical, (2021). Numerical and Experimental Analysis of the Creep Behaviour of Polyethylene Polymers. *Proceedings of the 4th International Conference on Numerical Modelling* in Engineering 49–80. https://link.springer.com/chapter/10.1007/978-981-16-8806-5_5?fromPaywallRec=true
5. Shekarchi W. A., Pudleiner D. K., Alotaibi N. K., Ghannoum W. M., Jirsa J. O. (2020). Carbon Fiber-Reinforced Polymer Spike Anchor Design Recommendations. *Structural Journal.* 117(6), 171-182. URL: https://doi.org/10.14359/51728065.
6. EN 1992-4 (1992). https://uscc.ua/uploads/page/images/normativnye%20dokumenty/dstu/proektuvannya-mk-mizhnarodna-gilka-standarty/dstu-n-b-en-1992-1-2.pdf
7. Wei W., Yuan Y., Gao X. (2020). Efects of Large Deformation and Velocity Impacts on the Mechanical Behavior of Filled Rubber: *Microstructure-Based Constitutive Modeling and Mechanical Testing. Polymers* 12, 2322; https://doi.org/10.3390/polym12102322
8. Budhe, S. (2019). An updated review of adhesively bonded joints in composite materials. Journal of Adhesion Science and Technology https://www.researchgate.net/publication/309271902_An_updated_review_of_adhesively_bonded_joints_in_composite_materials
9. Viljoen D., Fischer M., Kühnert I., Labuschagné J. (2021). The Tensile Behaviour of Highly Filled High-Density Polyethylene Quaternary Composites: Weld-Line Effects. DIC Curiosities and Shifted Deformation Mechanisms. Polymers 13, 527. https://doi.org/10.3390/polym13040527
10. Золотов С. М., Пустовойтова О.М., Фірсов П.М. (2019). Термореактивні смоли холодного затвердіння для відновлення та реконструкції промислових і цивільних будівель. Монографія; ХНУМГ ім. О. М. Бекетова, 184. Zolotov S. M. Pustovoitova O.M., Firsov P.M. (2019) Termoreaktyvni smoly kholodnoho zatverdinnia dlia vidnovlennia ta rekonstruktsii promyslovykh i tsyvilnykh budivel. [Cold-curing thermosetting resins for the restoration and reconstruction of industrial and civil buildings] monohrafiia: KhNUMH im. O.M. Beketova, 184. [in Ukrainian]
11. Трикоз Л. В., Камчатна С. М., Пустовойтова О. М. (2019). Вплив виду та кількості наповнювача на деформативні властивості акрилового композиційного матеріалу для ремонту бетонних конструкцій. Вісник ОДАБА. 74, 122-128. Trykoz L.V., Kamchatna S.M., Pustovoitova O.M (2019) Vplyv vydu ta kilkosti napovniuvacha na deformatyvni vlastyvosti akrylovoho kompozytsiinoho materialu dlia remontu betonnykh konstruktsii. [The influence of the type and amount of filler on the deformation properties of acrylic composite material for the repair of concrete structures] Visnyk ODABA. 74. 122-128. [in Ukrainian] http://dx.doi.org/10.31650/2415-377X-2019-74-122-128.
12. Ferdinánd, M.; Várdai, R.; Móczó, J.; Pukánszky, B. (2021) Deformation and Failure Mechanism of Particulate Filled and Short Fiber Reinforced Thermoplastics: Detection and Analysis by Acoustic Emission Testing. Polymers, 13, 3931. https://doi.org/10.3390/polym13223931
13. Rajhi, A.A. (2022) Mechanical Characterization of Hybrid Nano-Filled Glass/Epoxy Composites. Polymers, 14, 4852. https://doi.org/10.3390/polym14224852
14. Quadflieg T., Srivastava V. K., Gries T., Bhatt S. (2023) Mechanical Performance of Hybrid Graphene Nanoplates, Fly-Ash, Cement, Silica, and Sand Particles Filled Cross-Ply Carbon Fibre Woven Fabric Reinforced Epoxy Polymer Composites Beam and Column. Journal of Materials Science Research, 12 (1), 22-35. https://doi.org/10.5539/jmsr.v12n1p22

Pustovoitova Oksana, Ph.D., Associate professor, Computer graphics Department,
Phone: +38 (096) 417-89-48,
e-mail: oksana_pustov@ukr.net,
ORCID: http://orcid.org/0009-0003-4774-6686

[1]Kharkov National Automobile and Highway University, 25, Yaroslava Mudrogo str., Kharkiv, 61002, Ukraine

Моделювання та дослідження кінетики деформацій у полімерних клейових системах

Анотація. проблема. *У статті досліджується зміна межі пружності та межі міцності акрилового клею у часі – від максимального значення (короткочасна міцність) до мінімального (межа тривалого опору). Експериментально вивчено розвиток деформацій у зразках при постійних навантаженнях, що становлять від 0,2 до 0,85 від руйнівних. Показано, що при напругах нижче межі тривалого опору крива деформацій включає дві ділянки: миттєві деформації і в'язкі, що розвиваються в часі. Руйнування відбувається внаслідок накопичення пошкоджень (тріщин, дефектів), причому його швидкість залежить від рівня напруги та конфігурації клейового шва.* ***Мета.*** *Метою дослідження є встановлення закономірностей зміни межі пружності та межі міцності акрилового клею в часі під дією постійного навантаження, а також аналіз процесу накопичення пошкоджень у клейових з'єднаннях залежно від рівня напруги.* ***Методологія.*** *Експериментальне дослідження передбачало випробування зразків акрилового клею при сталих навантаженнях, що складали від 20 % до 85 % від короткочасної міцності (руйнівного навантаження). Спостерігали за розвитком деформацій у часі та фіксували зміну характеру руйнування.* ***Результати.*** *Встановлено, що при напругах, менших за межу тривалого опору, крива деформацій має дві характерні ділянки: миттєві (еластичні) деформації та в'язкі (часові), які розвиваються поступово. Показано, що руйнування відбувається внаслідок поступового накопичення мікропошкоджень, зокрема тріщин і дефектів, при цьому швидкість деградації залежить як від рівня навантаження, так і від геометрії клейового шва.* ***Оригінальність.*** *Робота вперше комплексно описує перехід від короткочасної до тривалої міцності акрилового клею в умовах постійного навантаження, з урахуванням впливу конфігурації з'єднання на швидкість руйнування..* ***Практична цінність.*** *Отримані результати можуть бути використані для прогнозування довговічності клейових з'єднань в конструкціях, що працюють в умовах постійного навантаження, зокрема в анкерних системах, і для оптимізації їх геометрії з метою підвищення надійності.*

Ключові слова: *повзучість, акриловий клей, полімерна клейова система, короткочасна міцність, межа тривалого опору, деформації, будівельні з'єднання*

Пустовойтова Оксана[1], к.т.н., доц. кафедри нарисної геометрії,
e-mail: oksana_pustov@ukr.net,
тел: +38096-41-789-48,
ORCID: http://orcid.org/0009-0003-4774-6686

[1]Харківський національний автомобільно-дорожній університет, 61002, Україна, м. Харків, вул. Ярослава Мудрого, 25.