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STRAIN HARDENING OF REINFORCEMENT IN REINFORCED CONCRETE ELEMENTS AFTER RESIDUAL DEFORMATIONS

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Abstract: The article presents a comprehensive study of the influence of strain hardening (work hardening effect) on the mechanical properties of thermally strengthened A500C reinforcement in reinforced concrete structures. The use of stepwise testing with the digital image correlation (DIC) method allowed detailed data to be obtained on local stress–strain processes, accumulation of residual plastic deformations, and changes in the yield strength of reinforcement under repeated loading. Experimental results showed that after primary overloading, the reinforcement retains significant residual deformations, which shift the stress–strain curve along the strain axis, while the elastic properties of the steel remain practically unchanged. It was found that the yield strength of the reinforcement under repeated loading increases by 10–20% due to strain hardening and partial stabilization of the dislocation structure of the crystal lattice. The interaction of reinforcement with concrete in the crack zone, including mechanical interlock and adhesion effects, was studied, contributing to local stiffness increase and actual load-bearing capacity of the elements. The proposed methodology allows quantitative assessment of the reinforcement's residual load-bearing capacity after overloading, partial damage, or restoration, which has practical significance for reconstruction, strengthening, and modernization of reinforced concrete structures. The study results confirm the necessity of considering the work hardening effect and residual deformations when evaluating residual capacity and safety of structures, especially bridges, high-rise buildings, and objects in seismically active areas.
Keywords: Reinforced concrete structures, load-bearing capacity, reinforcement, yield strength, strain hardening (work hardening effect).

1. INTRODUCTION

Reinforced concrete (RC) structures play a crucial role in modern construction due to the combination of the high compressive strength of concrete and the ability of steel reinforcement to effectively resist tensile forces (Andriichuk et al., 2021; Blikharskyy et al., 2021; Dmytrenko et al., 2023). The presence of reinforcement enables the creation of structural elements operating under complex stress states, ensuring the reliability and durability of the most critical buildings and structures (Dmytrenko et al., 2016; Dorofeyev and Pushkar, 2023; Katunský et al., 2015). Design codes emphasize the necessity of accurately considering the properties of reinforcement, namely: cross-sectional area, yield strength, ductility, and modulus of elasticity, since these parameters determine the load-bearing capacity of elements and the ultimate limit states of structures (DBN, 2011; DSTU, 2011; Eurocode, 2004; Eurocode, 2005; Koteš et al., 2023; Khmil et al., 2023).

The mechanical properties of reinforcing steel significantly affect the calculation and predicted behavior of structural elements (Blikharskyy et al., 2019; Lipinski & Wach, 2020; Malvar, 1998). The most critical parameter of steel is its yield strength, which marks the transition of the material from elastic to plastic behavior (Kos et al., 2017; Kotes et al., 2020; Lenkovskiy et al., 2017; Lipiński 2021). Exceeding the yield point due to overloading is accompanied by the formation of residual deformations in reinforcement, which alter the initial stress–strain state of the structure (Ostash et al., 2011; Koteš et al., 2022; Vatulia et al., 2020; Zahuranec et al., 2023). Residual deflections and stress redistribution in cross-sections lead to a reduction in element stiffness, which may impair the serviceability of a structure (Klym et al., 2025; Kopiika et al., 2024). However, at the microstructural level, much more complex processes occur in steel, which not only fix plastic deformations but also lead to changes in its strength properties (Borysovska and Podrezov, 2006; Danylenko et al., 2015; Bandyopadhyay et al., 2019; Gutierrez-Urrutia and Raabe, 2011).

The physics of processes accompanying plastic deformation of steel is explained by the movement and accumulation of dislocations within the crystal lattice. Once the yield strength is exceeded, dislocation density increases sharply, hindering further displacement of atomic planes. This phenomenon is known as strain hardening (work hardening effect) (Nesterova et al., 2001; Basiruddin et al., 2016).

During loading, the internal structure of steel undergoes sequential transformations reflected in the nature of dislocation formations and grain morphology (Stechyshyn et al., 2015; Pietrzak, 2024). At the initial stages of deformation, a dense network of dislocations develops, which gradually complicates, forming chaotic tangles and characteristic stress accumulation zones. The further progress of the process promotes the formation of dislocation dipoles and partial dislocations, indicating activation of slip mechanisms and redistribution of internal stresses. With the increase in deformation, the structure becomes more ordered: slip bands, subgrain structures, as well as low-angle and high-angle boundaries appear, gradually transforming into stable elements of deformation microstructure. This evolutionary process illustrates the transition from chaotic dislocation accumulation to the formation of an ordered system of substructural boundaries, which reflects the mechanism of work hardening and explains the improvement of steel strength characteristics under dynamic and cyclic loading (Fig. 1).

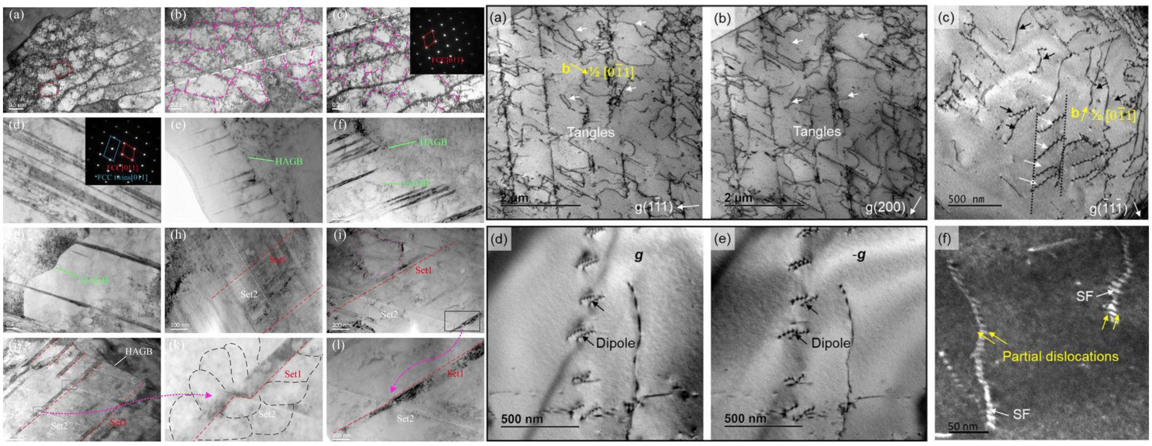


Fig. 1. Demonstration of the development of the deformation structure after loading

Research findings indicate that the relative elongation at maximum stress is considered an important criterion of reinforcement steel ductility, and its correlation with the strengthening index provides a better explanation of the mechanisms of strain hardening in reinforcing bars (Hortigón et al., 2019).

As a result of strain hardening, the material exhibits increased strength and yield limit under repeated loading, although at the same time its ductility and fracture toughness decrease (Chaboche, 2008). For reinforcement steels, the strain hardening effect has been confirmed by numerous tests: under repeated loading, the “stress–strain” curve shifts towards higher stresses, which indicates increased strength (Cadoni et al., 2013).

Experimental studies of reinforcing bars show that after initial overloading and fixation of residual deformations, the load-bearing capacity under subsequent loading may even increase. Tests of beams with pre-plastically deformed reinforcement demonstrate the presence of an additional load-bearing reserve due to strain hardening. At the same time, the effect is dual: the increase in strength is accompanied by the loss of ductility, which reduces the energy absorption capacity and increases the risk of brittle fracture, especially under cyclic or seismic loading (Russell, 2013).

The behavior of reinforcement after residual deformations is also affected by residual stresses formed during production and service. In ribbed bars, a non-uniform distribution of residual stresses is observed — from tensile in the core to compressive near the surface and ribs, which influences bond with concrete and fatigue resistance (Robl et al., 2023). Pre-plastic deformation may alter the bond conditions in the “reinforcement–concrete” system: at low levels of residual deformation, it is maintained, but under significant plastic strains it degrades, reducing the effectiveness of stress transfer between materials.

The practical implications of this phenomenon are significant. On the one hand, strain hardening provides a certain “reserve” of load-bearing capacity in reinforced concrete elements even after exceeding the yield strength of reinforcement. On the other hand, reduced ductility lowers deformation capacity and durability (Ho et al., 2005). This is particularly critical for bridges, high-rise structures, and constructions operating in seismic regions. Therefore, modern approaches to assessing residual capacity include not only stress–strain state analysis, but also the study of microstructural changes, ductility loss, corrosion effects, and cyclic loading.

Recent research proposes mathematical models for predicting the behavior of pre-plastically deformed reinforcement. These models account for modifications in the “stress–strain” curves, residual stresses, bond with concrete, and the effect of multiple loading cycles. The application of numerical simulations and machine learning methods enables quantitative assessment of the relationship between residual plastic strain magnitude and yield strength change, which is a promising development direction (Phetlam and Uthaisangsuk, 2015). At the same time, the need for large-scale experiments and standardized methodologies remains relevant, since such studies are essential to ensure the reliability of design solutions and adequacy of regulatory frameworks (DBN V.1.2-14, 2009; Eurocode, 2002).

Thus, strain hardening of reinforcement after residual deformations is a complex multi-factor phenomenon with both positive (strength enhancement) and negative consequences (reduced ductility and fracture toughness). Understanding these processes is a prerequisite for the proper assessment of the residual capacity of reinforced concrete structures, ensuring their safety, and developing strengthening methods (Blikharskyi, 2008). Further research should focus on the quantitative evaluation of strain hardening effects in different reinforcement grades, investigation of fatigue behavior after overloading, and the creation of unified approaches for inspection and repair of structures.

2. METHODOLOGY OF EXPERIMENTAL TESTS

The study on the investigation of strain hardening (the Bauschinger effect) in reinforcement was carried out using six reinforced concrete beams (three beams with varying diameters of milled reinforcement bars and their twin beams) with dimensions of 2100×200×100 mm and the following structural configuration: the main reinforcement bars of Ø20 A500S were milled down to actual diameters of Ø14 and Ø18 mm, while Ø25 A500S bars were reduced to Ø20 mm. The transverse reinforcement consisted of U-shaped stirrups with a diameter of 6 mm, grade A240C, spaced at 75 mm. The concrete used in the beams was of strength class C35/45. According to cube tests, its compressive strength was 48.2 MPa. The reinforcement layout of the experimental reinforced concrete beams is shown in Figure 2.

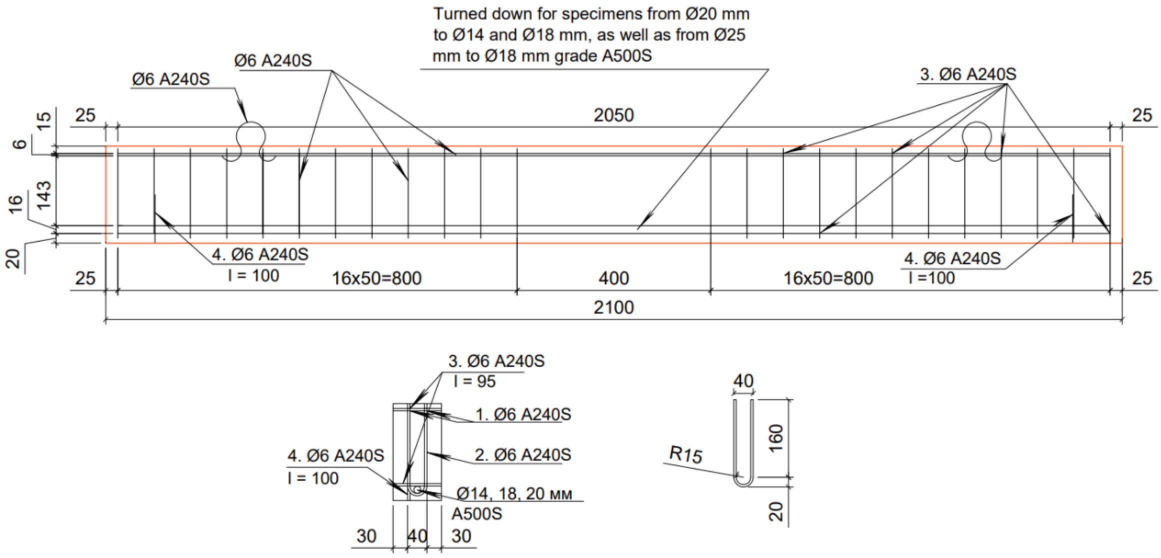


Fig. 2. Reinforcement of reinforced concrete beams

A notch measuring 50×250 mm was provided at the midspan of the experimental beams prior to concreting. This opening was intended to allow access to the tensile reinforcement for the investigation of the actual and precise tensile strain values at any loading stage of the structure using the digital image correlation (DIC) method (Figure 3).

Fig. 3. View of the opening in the tested beams for access to the tensile reinforcement when using the DIC method

The experimental specimens were tested according to a simply supported single-span beam scheme with a span of l0=1900l_0 = 1900l0=1900 mm, subjected to two concentrated loads applied at one-third of the span. Consequently, the distance from each support to the point of load application, as well as the distance between the two applied loads, was 633 mm (Figure 4).

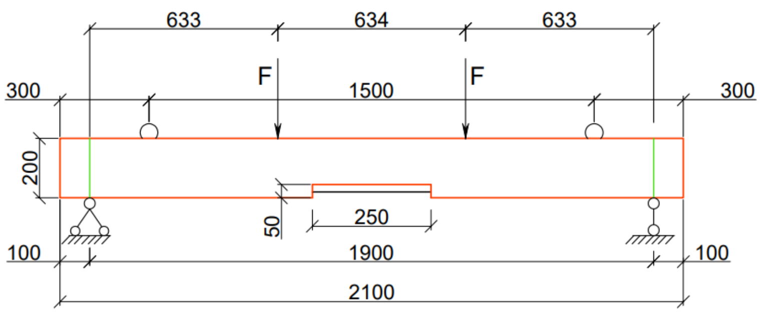


Fig. 4. General view of the specimens under loading with two concentrated forces

The overall view of the testing setup with installed instruments for the experimental study is shown in Figure 5.

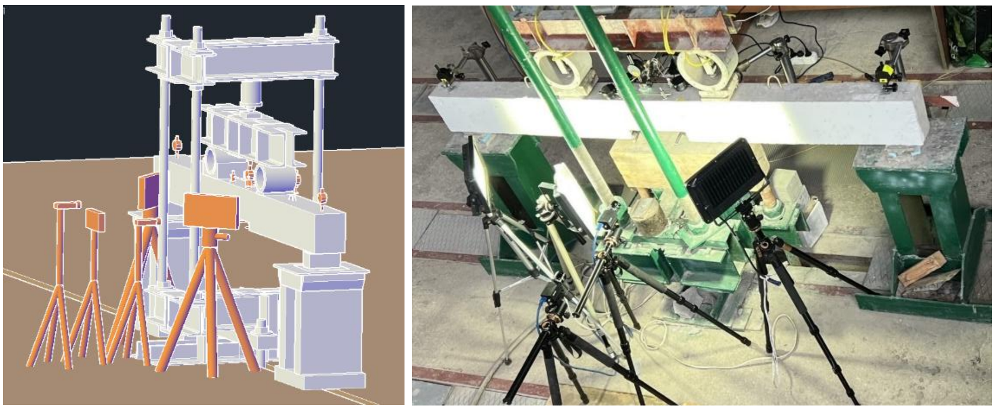


Fig. 5. Test stand layout and instrumentation arrangement

The results of the reinforcement deformability and its analysis were obtained using the Digital Image Correlation (DIC) method. This method was applied to study a 200 mm long section of the reinforcement. Strain measurements were performed using a specially prepared speckle pattern applied to the investigated area. To determine the strains, Vic-2D software was employed, which requires two distinct colors for tracking; subsequently, the software analyzes the displacements of individual subsets while accounting for measurement errors and corrections.

Prior to testing, the specimens were prepared by cleaning the reinforcement from any foreign elements, including corrosion, scale from machining, and residual concrete. The next step involved creating a black background with white speckles on the investigated area to implement the DIC methodology. The black coating was applied using matte spray paint (Figure 6), followed by the application of a speckle pattern of white dots using an airbrush connected to a compressor (Figure 7). The dot diameter ranged from 0.2 to 0.4 mm, which was determined based on the optimal pixel size relative to the camera resolution and the distance between the camera and the investigated area.

Fig. 6. Application of speckles on the working reinforcement using an airbrush

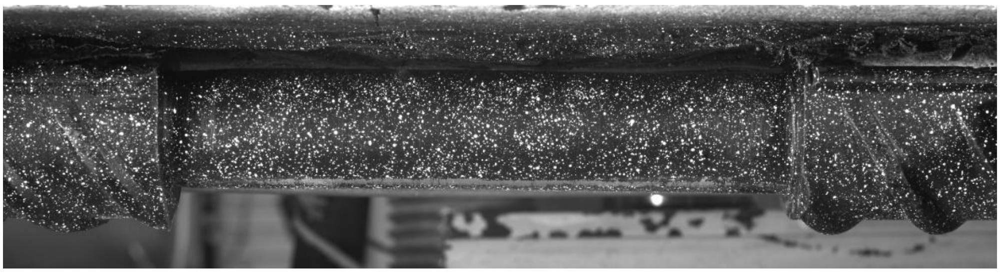


Fig. 7. Speckles applied on the reinforcement

To investigate and determine the strains in the examined section of the tensile reinforcement within the pure bending zone, a monochromatic camera from the Canadian company Flir, model *Grasshopper 3*, equipped with a Computar F25/2.8 lens, was used (Figure 8).

Fig. 8. View of the camera capturing deformations in the tensile reinforcement

During the configuration process, adjustments were made to the shutter speed, gamma, exposure, and a range of other parameters. The purpose of this procedure was to adapt the camera settings to the existing lighting conditions in order to achieve maximum background clarity and high contrast in the investigated area.

The grinding of the reinforcement bars was carried out to simulate corrosion processes that occur over time during service, which reduce the cross-section of the bars and destroy the thermally hardened layer of the reinforcement. To determine the actual yield strength and ultimate strength of the ground reinforcement bars, tests were conducted on the same bars used in the reinforced concrete beams on a tensile testing machine, and these values are presented in Table 1.

Table 1

Results of Tests of Reinforcement Bars

Ø*init*,, mm.	**Ø*ef*, mm**	**Results of Experimental Studies**							
		$\sigma_{0.2i}$, MPa, sample			**$\bar{\sigma}_{0.2i}$, MPa, structural layer**	**$\sigma_{u,i}$, MPa, sample**			**$\bar{\sigma}_{u,i}$, MPa, structural layer**
		1	**2**	**3**		**1**	**2**	**3**	
20	20	584.0	582.5	580.5	582.3	716.0	718.0	719.5	717.8
	14	480.5	475.0	476.5	477.3	611.0	614.5	612.0	612.5
	18	559.0	556.5	559.0	558.2	670.5	673.0	674.0	672.5
25	20	532.0	531.5	530.5	531.3	607	602.5	603.0	604.2

The methodology of the experimental investigation was based on a staged testing of reinforced concrete beams using the Digital Image Correlation (DIC) method. The primary objective was to monitor changes in the stress–strain state of the reinforcement during both the initial and repeated loading and to identify the strain-hardening (work-hardening) effect that occurs when steel enters the plastic region. The chosen experimental scheme enabled the capture of local deformation processes in the reinforcement, determination of their development patterns, and quantitative assessment of the yield strength changes during repeated loading.

The study of reinforcement strain-hardening was conducted in two loading stages on the same reinforced concrete element. The methodology employed DIC, allowing for the tracking of localized deformation changes in the reinforcement throughout the entire testing cycle. The main aim of the experimental program was to identify alterations in the stress–strain characteristics of the reinforcement after the initial transition beyond the yield point and to determine the work-hardening effect caused by the accumulation of residual deformations.

During the first stage, the specimen was loaded until the reinforcement in the tensile zone exceeded its yield strength. Real-time deformation monitoring using the DIC system enabled precise identification of the moment when the reinforcement transitioned from elastic to plastic behavior. The DIC method provided spatial strain distribution and allowed recording the reinforcement yield strength during the primary loading cycle, as shown in Table 1. Upon exceeding this limit, the specimen was loaded until failure in the concrete compression zone, resulting in residual deformations due to reinforcement stress levels of 800–1000 MPa. These data served as the basis for subsequent comparison with the repeated test.

After reaching the ultimate state and failure of the concrete compression zone, the damaged section of the reinforced concrete beam was restored. Restoration of the concrete compression zone preserved the reinforcement in its post-primary loading condition, creating conditions for the repeated assessment of its load-bearing capacity. This approach allowed direct experimental verification of steel strain-hardening, as the second loading cycle involved the same reinforcement bar that had already undergone plastic deformation. It should also be noted that after the initial testing, the failure of the concrete compression zone occurred. The restoration method for the compressed concrete zone consisted of cutting out the damaged region using tools across the full width of the RC beam and to a depth of 60 mm along the height of the cross-section, as well as longitudinally along the beam for 450 mm from the midspan toward the supports. Afterward, the removed volume of damaged concrete was filled with the high-strength repair mortar Sika MonoTop-4012.

In the second loading cycle, the methodology remained unchanged: reinforcement deformations were monitored using DIC, allowing the tracking of changes in the stress–strain diagram relative to the primary test.

The applied experimental scheme enabled the observation of changes in the mechanical properties of the reinforcement during repeated loading and the direct registration of strain-hardening (work-hardening) on the actual reinforced concrete specimen. The Digital Image Correlation method provided high accuracy in determining local deformations and allowed quantitative evaluation of the increase in load-bearing capacity.

3. RESULTS AND DISCUSSION

During the experimental investigation and subsequent analysis, it was established that after the initial loading of reinforced concrete bending elements with thermomechanically strengthened reinforcement of class A500C, residual plastic deformations were observed in the steel. These residual deformations were recorded using the Digital Image Correlation (DIC) method, which ensured high accuracy of the results and enabled a quantitative assessment of changes in the stress–strain state of the reinforcement after exceeding the yield point. The results indicate that, upon unloading, the reinforcement does not return to its original geometric configuration, demonstrating a partial loss of elastic properties and the formation of irreversible plastic deformations.

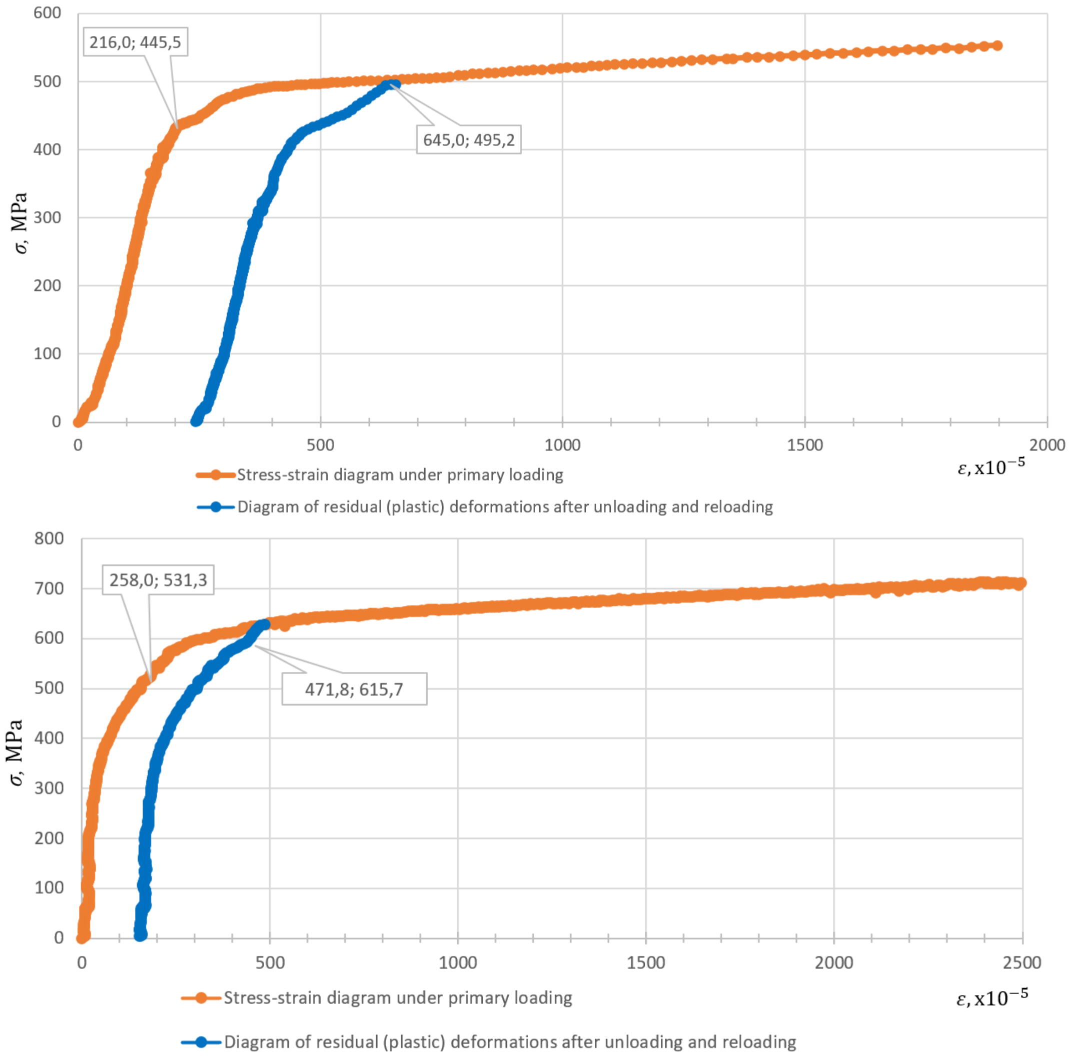
The repeated loading of the specimens accounted for the already existing residual deformations accumulated during the primary loading, which caused a shift of the stress–strain diagram (σ–ε) along the strain axis. The initial segment of the curve under repeated loading does not fully coincide with the primary elastic portion of the diagram, reflecting a modified development of the stress–strain state consistent with Hooke's law. However, the geometry of this segment remains nearly parallel to the original elastic curve, maintaining a similar modulus of elasticity within the limits of repeated elastic loading. This parallelism indicates that the elastic properties of the steel remain largely unchanged after primary loading, while the diagram shifts geometrically due to pre-existing plastic deformation.

It was observed that the yield strength of the reinforcement during repeated loading increased by 10–20% compared to the initial loading, as reflected in the obtained tensile diagrams for reinforcements of different diameters (Fig. 9). The increase in yield strength is explained by the combined effect of several physico-mechanical processes occurring within the steel structure as a result of prior plastic deformation.

Consequently, the yield strength of the reinforcement in repeated loading rises by 10–20% relative to the initial diagram (Fig. 9). This increase is attributed not only to the accumulation of plastic deformations but also to the formation of residual (secondary) stresses in the material structure induced by the primary loading, which generate an internal stress state capable of providing additional resistance to external forces during the subsequent loading cycle.

a)

b)



c)

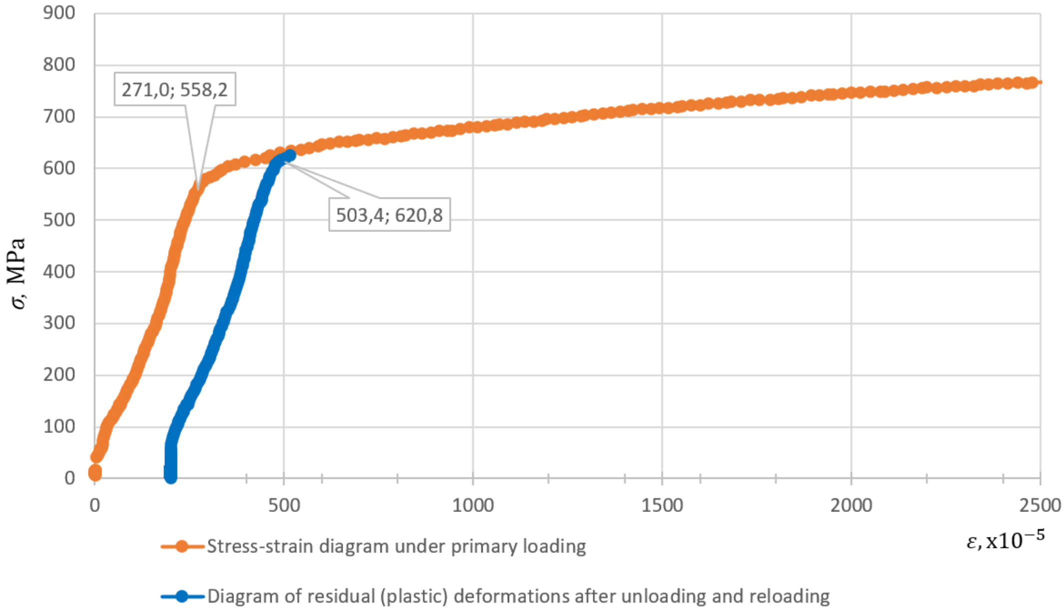


Fig. 9. Stress–strain diagram «σ-ε»: a) tensile diagram of reinforcement $Ø_{init}$,=20 mm., $Ø_{ef}$ =14 mm.; b) tensile diagram of reinforcement $Ø_{init}$,=25 mm., $Ø_{ef}$ =20 mm.; c) tensile diagram of reinforcement $Ø_{init}$,=20 mm., $Ø_{ef}$ =18 mm.

One of the key factors contributing to the increase in strength after the initial loading is the strain-hardening effect (work hardening) and partial stabilization of the dislocation structure in the steel's crystalline lattice. The physico-mechanical nature of this phenomenon is associated with structural rearrangements in the steel resulting from plastic deformation. When the yield point is exceeded, dislocation strengthening mechanisms are activated: the crystalline lattice becomes disrupted, dislocations accumulate and interact with one another and with other defects, hindering further dislocation movement. Consequently, a higher stress is required to initiate subsequent plastic flow, which manifests as an increased yield strength during repeated loading.

The prior loading of the element leads to the formation of a new deformation configuration that accounts for the material's accumulated strengthening. Experimentally observed increases in yield strength by 10–20% indicate that even partially damaged reinforcement can provide substantial residual resistance to external actions, which is particularly important when evaluating the residual load-bearing capacity of structures that have been overloaded or partially damaged.

The methodology for assessing the stress–strain state of reinforcement under repeated loading allows for a deeper understanding of steel strengthening mechanisms and the development of more accurate models for residual strength assessment. This is critical in the practice of reinforced concrete reconstruction and strengthening, where existing reinforcement that has already been in service is used. Ignoring residual deformations in such cases leads to conservative but imprecise evaluations of the structural condition, whereas accounting for the strain-hardening effect provides a more realistic assessment of additional strength reserves.

In real specimens, the concrete structure is often heterogeneous, and the interaction between reinforcement and concrete in cracks, including mechanical interlock and bond effects, leads to local stiffness increases. Traditional analytical models do not account for

these internal structural features and additional resistance, which results in higher actual load-bearing capacity of the specimens.
Experimental studies revealed actual strength reserves not considered in basic theoretical calculations, which can be incorporated into modern methods for restoring and assessing the residual strength of repaired or damaged structures. The proposed approach, which considers residual reinforcement deformations after its initial loading, allows for refinement of stress–strain diagrams and an accurate representation of the actual strength of damaged and restored elements. This analysis is novel for the practice of reinforced concrete design considering damaged and deformed reinforcement. The results demonstrate that traditional analytical methods prescribed by standards (DBN, 2011; DSTU, 2011) may underestimate the residual capacity of structures after partial damage because they do not account for the strengthening occurring due to the strain-hardening effect. Developing models that incorporate this effect will improve the accuracy of residual capacity assessments.
Thus, accounting for residual deformations in the analysis of repeatedly loaded elements provides a more precise picture of the actual stress–strain state and revises approaches to determining the residual strength of structures. The obtained results have practical significance for improving diagnostic and assessment methods for reinforced concrete structures during restoration, modernization, or strengthening.

4. CONCLUSION

The conducted study demonstrates a comprehensive approach to assessing the influence of strain hardening (work hardening effect) on the mechanical properties of reinforcement in reinforced concrete structures. The use of thermomechanically strengthened reinforcement of class A500C and a stepwise testing procedure with the application of the Digital Image Correlation (DIC) method allowed obtaining detailed data on local stress–strain processes, accumulation of residual deformations, and changes in the yield strength of reinforcement under repeated loading.
The results of the experimental investigations confirm that, after the initial overload, the reinforcement retains residual plastic deformations, which cause a shift of the stress–strain curve along the deformation axis. The elastic properties of the steel remain practically unchanged; however, the geometry of the deformation curve shifts due to the accumulated plastic deformations. It was established that the yield strength of the reinforcement during repeated loading increases by 10–20%, which is explained by the effect of strain hardening and partial stabilization of the dislocation structure of the crystalline lattice. This process reflects the physico-mechanical nature of steel strengthening under plastic deformation and the accumulation of residual stresses within the material structure.
The stepwise loading methodology using DIC enabled real-time tracking of local deformation processes in the reinforcement, quantitative assessment of the increase in load-bearing capacity, and direct observation of the work hardening effect in actual reinforced concrete specimens. The study demonstrated that even partially damaged reinforcement retains a significant strength reserve, which is of practical importance for evaluating the residual load-bearing capacity of structures after overloads, partial damage, or restoration.
Furthermore, it was found that the interaction between reinforcement and concrete in the crack zones, including mechanical interlock and adhesion effects, contributes to local

stiffness enhancement and actual load-bearing capacity of the elements, which conventional analytical models do not account for. This emphasizes the need to include the work hardening effect and actual residual deformations in modern assessment methodologies for the technical condition and restoration of reinforced concrete structures.

The obtained results have significant scientific and practical implications. They allow for more accurate modeling of the residual strength of elements after overload, evaluation of the load-bearing capacity reserve, and development of adequate approaches for reconstruction, strengthening, and modernization of structures. Considering the strain hardening effect provides a more realistic assessment of the condition of reinforced concrete structures and contributes to increasing their reliability, durability, and safety, particularly in bridges, high-rise buildings, and structures operating in seismically active regions.

Thus, the study confirms that the work hardening effect of reinforcement is an important factor to be considered in the design, evaluation of residual capacity, and strengthening of reinforced concrete elements. Accounting for microstructural changes, residual deformations, and internal stresses of the material allows for improving the accuracy of structural behavior predictions under complex operating conditions and optimizing methods of repair and restoration.

REFERENCES

Andriichuk, O., Yasiuk, I., Uzhehov, S., Palyvoda, O., 2021. *Experimental Research of Strength Characteristics of Steel Fiber Reinforced Concrete Gutters and Modeling of Their Work Using the Finite Element Method*. Lecture Notes in Civil Engineering, 100, 1–8. DOI: 10.1007/978-3-030-57340-9_1

Bandyopadhyay, K., Lee, J., Shim, J. H., Hwang, B., Lee, M. G., 2019. *Modeling and experiment on microstructure evolutions and mechanical properties in grade 600 MPa reinforcing steel rebar subjected to TempCore process*. Materials Science and Engineering: A, 745, 39-52. doi:10.1016/j.msea.2018.12.079

Basiruddin, S.K., Khan, A.K., Lenka, S., Syed, B., Chakraborty, J., Chakrabarti, D., Kundu, S., 2016. *Effect of microstructure and texture on the impact transition behaviour of thermo-mechanically treated reinforcement steel bar*. Mater, Des, 90, 1136-1150. doi:10.1016/j.matdes.2015.11.053

Blikharskyi, Z.Ya., 2008. *Reconstruction and strengthening of buildings and structures*. Textbook, Lviv, Lviv Polytechnic Publishing House.

Blikharskyy, Y., Selejdak, J., Bobalo, T., Khmil, R., Volynets, M., 2021. Influence of the percentage of reinforcement by unstressed rebar on the deformability of pre-stressed RC beams. Production Engineering Archives, 27(3), pp. 212–216. DOI: 10.30657/pea.2021.27.28

Blikharskyy, Z., Selejdak, J., Blikharskyy, Y., Khmil, R., 2019. *Corrosion of Reinforce Bars in RC Constructions*, System Safety: Human - Technical Facility – Environment, 1(1), 277-283, DOI: 10.2478/czoto-2019-0036

Borysovska, E.M., Podrezov, Yu.N., 2006. *Analysis of the Dislocation Annihilation Process in the Case of their Chaotic Disposition*. Kiev: Collection «Mathematical Models and a Computational Experimenting Materials Science», 8, 116.

Cadoni, E., Dotta, M., Forni, D., Tesio, N., Albertini, C., 2013. *Mechanical behaviour of quenched and self-tempered reinforcing steel in tension under high strain rate*. Materials & Design, 49, 657-666.

Chaboche, J.L., 2008. *A review of some plasticity and viscoplasticity constitutive theories*. International journal of plasticity, 24(10), 1642-1693. doi:10.1016/j.ijplas.2008.03.009

Danylenko, M.I., Podrezov, Yu.M., Firstov, S.A., 2015. *The Influence of Strain Degree on the Structural Transformations and Mechanical Properties of the Low-Carbon Steel 20Kh*. Lutsk: Inter-University Collection "NAUKOVY NOTATKI", 49, 42-46.

DBN V.1.2-14:2009 *General principles for ensuring the reliability and structural safety of buildings, structures, building constructions, and foundations*. Kyiv: Ministry of Regional Development and Construction of Ukraine, 2009. 43.

DBN V.2.6-98:2009, 2011. *Concrete and reinforced concrete structures. General design provisions*. – Kyiv: Ministry of Regional Development, Construction, and Housing and Communal Services of Ukraine.

Dmytrenko, Y., Genzerskiy, Y., Yakovenko, I., Bakulin, Y., 2023. *Strength analysis of normal cross-sections of reinforced concrete structures in uniaxial bending by Wood-Armer method in LIRA SAPR software*. AIP Conference Proceedings, 2678, 020006. DOI: 10.1063/5.0118680

Dmytrenko, Y., Yakovenko, I., Fesenko, O., 2016. *Strength of eccentrically tensioned reinforced concrete structures with small eccentricities by normal sections*. Scientific Review Engineering and Environmental Sciences, 30(3), 424–438. DOI: 10.22630/PNIKS.2021.30.3.36

Dorofeyev, V., Pushkar, N., 2023. *The Bearing-Capacity of Precast Beams with Vertical Contact Plane*. Lecture Notes in Civil Engineering, 290, 67–75. DOI: 10.1007/978-3-031-14141-6_7

DSTU B V.2.6-156:2010, 2011. *Building and civil engineering structures. Concrete and reinforced concrete structures made of heavy concrete. Design rules.* – Kyiv: Ministry of Regional Development, Construction, and Housing and Communal Services of Ukraine.

Eurocode 2: *Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings*. EN 1992-1-1:2004. – Brussels: CEN, 2004.

Eurocode 2: *Design of Concrete Structures – Part 2: Concrete Bridges – Design and Detailing Rules*. EN 1992-2:2005. – Brussels: CEN, 2005.

Eurocode EN 1990:2002, 2002, *Basis of structural design*. Brussels: European Committee for Standardization (CEN), 87.

Gutierrez-Urrutia, I., Raabe, D., 2011. *Dislocation and twin substructure evolution during strain hardening of an Fe–22 wt.% Mn–0.6 wt.% C TWIP steel observed by electron channeling contrast imaging*. Acta materialia, 59(16), 6449-6462. doi:10.1016/j.actamat.2011.07.009

Ho, J.C.M., Au, F.T.K., Kwan, A.K.H., 2005. *Effects of strain hardening of steel reinforcement on flexural strength and ductility of concrete beams*. Structural Engineering and Mechanics, 19(2), 185–198. doi:10.12989/sem.2005.19.2.185

Hortigón Fuentes, B., Gallardo Fuentes, J.M., Nieto García, E.J., López, J.A., 2019. *Strain hardening exponent and strain at maximum stress: Steel rebar case*, Construction and Building Materials, 196, 175-184. doi:10.1016/j.conbuildmat.2018.11.082.

Katunský, D., Katunská, J., Tóth, S., 2015. *Possibility of choices industrial hall object reconstruction*. International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, 2(5), 389–396.

Khmil, R., Blikharskyy, Z., Vegera, P., & Kopiika, N. 2023. Bearing capacity of reinforced concrete beams with and without damages of rebar. Production Engineering Archives, 29(3), 298–303. https://doi.org/10.30657/pea.2023.29.34

Klym, A., Blikharskyy, Y., Gunka, V., Poliak, O., Selejdak, J., Blikharskyy, Z., 2025. *An Overview of the Main Types of Damage and the Retrofitting of Reinforced Concrete Bridges*. Sustainability, 2071-1050, 17(6). doi: 10.3390/su17062506

Kopiika, N., Klym, A., Blikharskyy, Y., Katunský, D., Popovych, V., Blikharskyy, Z., 2024. *Evaluation of the stress-strain state of the RC beam with the use of DIC*. Production Engineering Archives, 30. doi: 10.30657/pea.2024.30.44

Kos, Ž., Gotal Dmitrović, L., Klimenko, E., 2017. *Developing a model of a strain (deformation) of a damaged reinforced concrete pillar in relation to a linear load capacity*, Tehnički glasnik, 11(4), 150-154, https://hrcak.srce.hr/190990

Koteš, P., Vavruš, M., Jošt, J., Prokop, J., 2020. *Strengthening of concrete column by using the wrapper layer of fibre reinforced concrete*, Materials, 13(23), 1-21, 5432, DOI: 10.3390/ma13235432

Koteš, P., Vavruš, M., Raczkiewicz, W., 2022. *Innovative strengthening of RC columns using a layer of a fibre reinforced concrete*, Acta Polytechnica CTU Proceedings, 33, 309-315, DOI: 10.14311/APP.2022.33.0309

Koteš, P., Zahuranec, M., Vavruš, M., 2023. *Diagnostic and Design of Reconstruction of Building Váhostav*, Lecture Notes in Civil Engineering, 322, 165-174, DOI: 10.1007/978-3-031-26879-3_13

Lenkovskiy, T.M., Kulyk, V.V., Duriagina, Z.A., Kovalchuk, R.A., Topilnytskyy, V.H., Vira, V.V., Tepla, T.L., 2017. *Mode I and mode II fatigue crack growth resistance characteristics of high tempered 65G steel*. Archives of Materials Science and Engineering, 84(1), 34–41. DOI: 10.5604/01.3001.0010.3029

Lipiński, T., 2021. *Investigation of corrosion rate of X55CrMo14 stainless steel at 65% nitrate acid at 348 K*, Production Engineering Archives, 27(2), 108-111, DOI: 10.30657/pea.2021.27.13

Lipiński, T., Wach, A., 2020. *Influence of inclusions on bending fatigue strength coefficient the medium carbon steel melted in an electric furnace*, Production Engineering Archives, 26(3), 88-91, DOI: 10.30657/pea.2020.26.18

Malvar, L.J., 1998. *Review of static and dynamic properties of steel reinforcing bars*. Materials Journal, 95(5), 609-616.

Nesterova, E.V., Bacroix, B., & Teodosiu, C., 2001. *Experimental observation of microstructure evolution under strain-path changes in low-carbon IF steel*. Materials Science and Engineering: A, 309, 495-499. doi:10.1016/S0921-5093(00)01639-7

Ostash, O.P., Muravs'Kyi, L.I., Voronyak, T.I., Kmet', A.B., Andreiko, I.M., Vira, V.V., 2011. *Determination of the size of the fatigue prefracture zone by the method of phase-shifting interferometry*. Materials Science, 46(6), 781–788. DOI: 10.1007/s11003-011-9353-1

Phetlam, P., Uthaisangsuk, V., 2015. *Microstructure based flow stress modeling for quenched and tempered low alloy steel*. Materials & Design, 82, 189-199. doi:10.1016/j.matdes.2015.05.068

Pietrzak, A., 2024. *Effect of polypropylene fiber structure and length on selected properties of concrete*. Construction of Optimized Energy Potential, 13(1), 78-88. DOI: 10.17512/bozpe.2024.13.09

Robl, T., Hegele, P., Krempaszky, C., Werner, E., 2023. *Residual Stresses in Ribbed Reinforcing Bars*. Materials (Basel, Switzerland), 17(1), 26. doi:10.3390/ma17010026

Russell, A.P., 2013. *Strain Hardening of Reinforcement in Concrete Buildings during Earthquakes*. Proceedings of the New Zealand Concrete Industry Conference, Queenstown, New Zealand, 3-5.

Stechyshyn, M., Sanytskyy, M., Poznyak, O., 2015. *Durability properties of high volume fly ash self-compacting fiber reinforced concretes*. Eastern-European Journal of Enterprise Technologies, 2015, 3(11), pp. 49–53, DOI: 10.15587/1729-4061.2015.44246

Vatulia, G.L., Smolyanyuk, N.V., Shevchenko, A.A., Orel, Y.F., Kovalov, M.O., 2020. *Evaluation of the load-bearing capacity of variously shaped steel-concrete slabs under short term loading*. IOP Conference Series: Materials Science and Engineering, 1002(1), 012007. DOI: 10.1088/1757-899X/1002/1/012007

Zahuranec, M., Koteš, P., Kraľovanec, J., 2023. *The Influence of the Prestressing Level of the Fully Threaded Anchor Bar on the Corrosion Rate*, Buildings, 13(7), 1592, DOI: 10.3390/buildings13071592