

ANALYSIS OF IMPROPER USE OF MATERIALS AND STRENGTHENING SYSTEMS IN STRUCTURAL REHABILITATION

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Abstract. The effectiveness, reliability, and durability of structural strengthening interventions depend not only on the selected materials and design concepts but also on the quality of their application throughout the entire rehabilitation process. Strengthening measures are typically implemented on existing structures that already contain defects and damage accumulated during their life cycle, which significantly influences stress redistribution, bond behavior, and long-term performance. Under these conditions, even advanced strengthening systems may exhibit reduced effectiveness when design assumptions, technological requirements, or environmental influences are improperly considered.

This paper analyzes typical cases of improper application of materials and systems used for strengthening building structures, including traditional steel-based solutions, fiber-reinforced polymer (FRP) systems, and connection and anchorage products. Based on the synthesis of inspection practice, experimental evidence, and regulatory approaches consistent with Eurocode and ISO principles, the study systematizes technical, technological, and organizational errors arising at the stages of design, execution, and operation. Particular attention is given to the interaction between improper-use factors and the existing defect and damage context of structures.

A generalized classification of defects and damage is adopted as structured input for strengthening assessment, allowing improper application scenarios to be analyzed in relation to defect origin, location, development behavior, and structural impact. A functional-structural risk model is proposed to formalize the relationship between improper-use factors, defect and damage characteristics, and the resulting consequences for



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structural performance. The overall effectiveness of strengthening is interpreted as an integrated function of accumulated risks associated with material selection, execution quality, and existing structural condition.

The obtained results provide a basis for improving quality assurance procedures, reducing technological and operational risks, and supporting risk-oriented decision-making in structural rehabilitation. The proposed framework contributes to enhancing the reliability, resilience, and long-term performance of strengthened structures within a life-cycle-oriented approach.

Keywords: structural strengthening; improper application; defects; damage; steel strengthening; FRP systems; technical errors; risk factors; building rehabilitation.

INTRODUCTION

Structural strengthening is widely applied in the rehabilitation of buildings and structures subjected to aging, increased loads, environmental degradation, or accidental impacts. Modern practice employs both traditional materials, such as structural steel, and advanced solutions including high-strength steels, fiber-reinforced polymers

(FRP), and specialized anchoring and connection systems. These materials provide high mechanical performance and adaptability to diverse operational conditions. However, experience from construction practice and technical inspections shows that improper application of even state-of-the-art materials often leads to premature degradation, loss of bearing capacity, or reduced durability. Such deficiencies are primarily associated with human factors, insufficient assessment of environmental conditions, design inaccuracies, poor surface preparation, violations of installation technology, and non-compliance with regulatory requirements. Therefore, systematic analysis of typical errors in the application of strengthening materials is essential for improving the overall quality and reliability of rehabilitation projects.

ANALYSIS OF PREVIOUS RESEARCH

The problem of improper use of materials and strengthening systems in structural rehabilitation has been actively discussed in both national and international research over the last decades. Existing studies can be conditionally grouped into several main research directions:

- strengthening technologies and materials,
- execution quality and technological risks,
- behavior and failure mechanisms of strengthened elements,
- regulatory and methodological approaches to strengthening design.

A significant body of research emphasizes that the effectiveness of strengthening measures depends not only on the selected material system, but also on the compatibility between the strengthening elements and the existing structure, construction technology, and operating conditions. Analytical and experimental studies devoted to the application of composite materials in building reconstruction highlight the high sensitivity of externally bonded systems to surface preparation, adhesive properties, environmental exposure, and workmanship quality [1,2]. Experimental investigations [3, 4] confirmed that even minor deviations from recommended

installation procedures for FRP systems may lead to premature debonding or loss of composite efficiency.

Comparative studies between traditional steel strengthening and FRP-based solutions indicate that neither approach is universally optimal [5]. Their effectiveness strongly depends on boundary conditions, stress redistribution, and long-term durability, especially under cyclic loading and aggressive environments. Similar conclusions were reported in international state-of-the-art reviews on FRP strengthening of steel and reinforced concrete structures [6,7], where improper detailing of bonded joints and insufficient consideration of fatigue behavior were identified as key sources of structural vulnerability.

At the same time, improper application of traditional strengthening methods based on steel plates, steel profiles, and bolted or welded elements has been extensively reported in the literature. Studies addressing metal-based strengthening systems indicate that errors in detailing, insufficient corrosion protection, poor-quality welding, and inadequate consideration of fatigue and temperature effects can significantly reduce the durability and reliability of strengthened structures [2,7]. In many cases, strengthening elements designed to increase load-bearing capacity introduce additional stress concentrations or restraint effects, which may accelerate damage development in the existing structural members.

In European practice, the design of strengthening interventions is generally based on the fundamental principles of Eurocodes, including reliability concepts, limit state design, and load combinations. However, Eurocodes provide only a framework for structural safety and do not offer detailed guidance for externally bonded FRP systems or specific repair technologies. In this context, specialized documents play a critical role. The Italian guideline CNR-DT 202/2005 [9] provides one of the most application-oriented sets of requirements, covering material properties, bond behavior, surface preparation, installation procedures, and quality control for

FRP strengthening. The fib Bulletins, particularly Bulletin 14 [10] and the recent Bulletin 102 [11], propose a more generalized engineering methodology focused on durability, protection, repair strategies, and lifecycle performance of strengthened concrete structures. Eurocodes, in contrast, serve as a regulatory backbone that ensures consistency of safety requirements and structural verification but rely on complementary documents for technological implementation.

This fragmentation of the regulatory and methodological framework partly explains why strengthening failures still occur in practice. Structural calculations may fully comply with Eurocode principles, while deficiencies in material selection, installation technology, or quality control undermine the actual performance of the strengthening system. Several authors explicitly note that the weakest link in rehabilitation projects is often not the design model itself, but the execution stage and the interface between new and existing materials [6,7,10,11].

Recent publications also emphasize the critical role of connection and anchorage systems. Anchors, bolts, adhesive joints, and hybrid connections govern force transfer and composite action between strengthening elements and the existing structure. Improper installation, insufficient surface preparation, or material incompatibility at this level frequently control the failure mode of the entire strengthening system, regardless of the strength of the primary reinforcing material [3,6,11].

Despite the extensive literature on strengthening materials and design approaches, relatively few studies systematically address improper application scenarios across different strengthening technologies. Most publications focus on material behavior, numerical modeling, or isolated experimental results, while execution-related errors and their interaction with the existing technical condition of structures are often considered only indirectly.

In practice, strengthening measures are applied to structures that already contain defects and damage accumulated during their life cycle. These initial conditions govern stress

redistribution, bond behavior, and durability, and therefore significantly increase the sensitivity of strengthening systems to execution errors. From the perspective of Eurocode- and ISO-based assessment, defect origin, location, and development potential should be treated as structured input parameters for strengthening design. Neglecting these aspects may lead to solutions that are adequate in calculation but incompatible with the actual structural condition and long-term performance requirements.

The literature review reveals several unresolved issues that justify further research:

- the absence of a unified classification of improper application cases for different strengthening systems (steel, FRP, connection and anchorage products), explicitly linked to existing defects and damage;
- insufficient integration of execution quality, technological risks, and life-cycle priorities into strengthening decision-making;
- limited use of formalized models that relate implementation errors to performance loss, durability reduction, and overall effectiveness of strengthening;
- weak coupling between material-oriented research and construction-process-oriented studies.

Consequently, there is a need for a comprehensive analytical framework that links defect and damage characteristics, material selection, execution quality, and uncertainty factors within the context of structural rehabilitation.

PURPOSE AND METHODS

The purpose of the study is to systematize typical cases of improper use of strengthening materials and systems (steel-based strengthening, FRP systems, and connection/anchorage products) and to propose a formalized factor–risk representation that supports structured quality assurance and decision-making in frame rehabilitation during reconstruction.

The research combines:

- Analytical synthesis of inspection practice and published evidence on typical implementation errors and failure modes;
- Factor-based structuring of improper-use causes into three families: metal strengthening F^M , FRP strengthening F^F , and connection / anchorage products F^B ;
- Formalization of consequences (risks) as a function of factor sets and the observed defect/damage context;
- Life-cycle and priority-based framing through sets of priorities P_i and uncertainty risks F_i , to align quality assurance with reconstruction objectives.

MAIN PART

Any strengthening intervention is applied to an existing structure that already contains defects and damage accumulated during its life cycle. Each defect is characterized by its origin, extent, geometry, and potential for further

development, while damage reflects the evolution of these defects under mechanical, environmental, and эксплуатационных influences. Therefore, the effectiveness of strengthening systems cannot be assessed independently of the initial technical condition of the structure [2, 5, 14, 18-21, 34]. Based on the analysis of inspection results for various types of building structures, a generalized defect typology consistent with the principles of Eurocode (EN 1990, EN 1991) [12, 13] and ISO standards for condition assessment and asset management [14-16] was adopted. Defects are classified according to their origin (cause-related classification), including design deficiencies, manufacturing and execution errors, and non-compliance with operational requirements. In addition, defects are differentiated by their location within the structure (external or internal) and by their structural impact, i.e. their influence on load-bearing capacity, serviceability, and durability (Fig. 1) [2, 18, 20, 34,35].

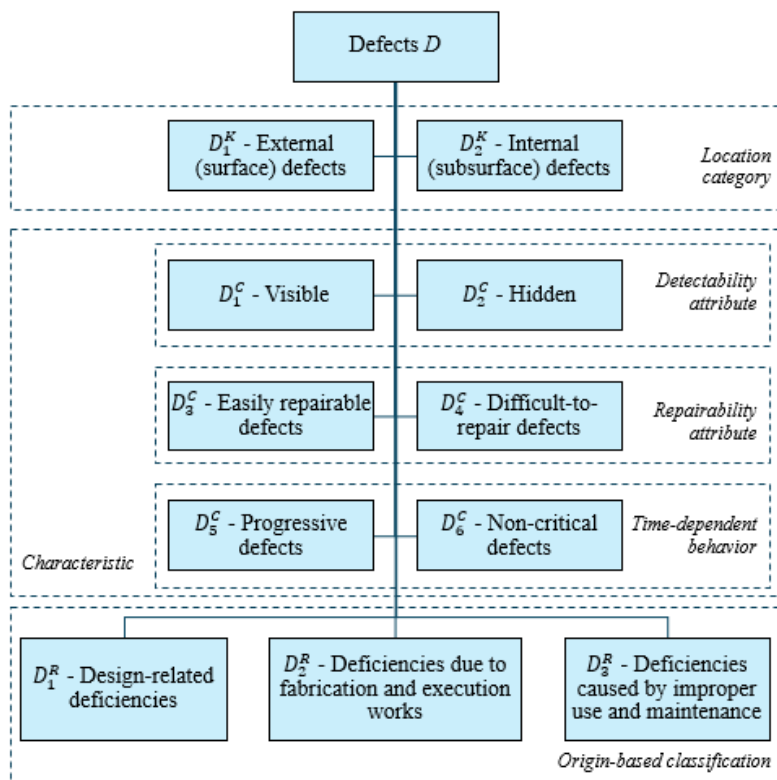


Fig. 1 General classification of structural defects by origin, category, and characteristic attributes

Рис. 1 Загальна класифікація дефектів в існуючих конструкціях

Within the proposed framework, defect categories (D^K) describe the physical location

of defects in the structural system, while defect characteristics (D^C) represent qualitative

attributes used for condition evaluation and decision-making. These characteristics include detectability, repairability, development over time, and influence on global structural performance. In accordance with Eurocode-based assessment philosophy, defect characteristics do not form independent classes; instead, they provide supplementary information required for reliability verification, risk-based assessment, and the selection of appropriate strengthening or rehabilitation measures [12,14].

The proposed defect classification and characterization framework is consistent with Eurocode concepts of reliability, limit states,

and deterioration mechanisms, providing structured input data for the assessment of existing structures and the selection of strengthening strategies.

In parallel, damage to structural elements is classified by the dominant type of external action, including mechanical, thermal, chemical, and explosive effects (Fig.2) [2, 11, 18, 20, 35]. Although this classification is common for both reinforced concrete and steel structures, the mechanisms of damage development and their consequences differ significantly depending on the structural material and detailing.

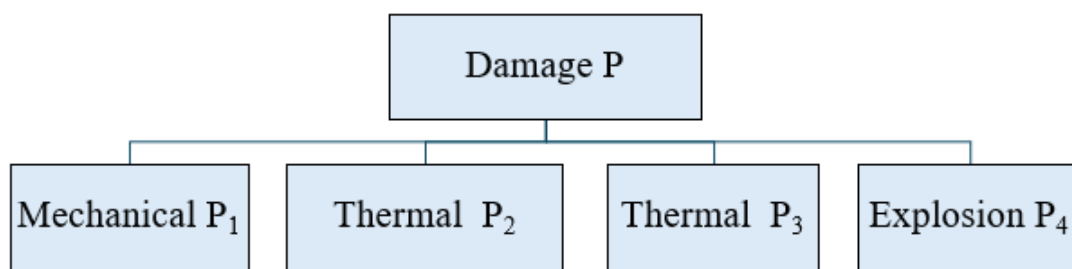


Fig. 2 General classification of structural damage by type of action

Рис. 2 Загальна класифікація пошкоджень за типами впливів

The presence and combination of specific defect and damage types form the initial boundary conditions for the selection and design of strengthening systems. Ignoring these conditions may lead to situations where a strengthening solution is structurally adequate in design but fails to perform as intended due to incompatibility with the existing state of the structure [1,5,14].

In contemporary practice of structural rehabilitation, both traditional materials (primarily steel) and high-performance engineering solutions are applied, including high-strength steels, fiber-reinforced polymer (FRP) systems, and specialized products for connections and anchorage [1–4, 10, 22, 23, 27, 28]. These materials are widely used due to their favorable mechanical properties, flexibility of application, and adaptability to various operational conditions.

However, results of technical inspections and numerous scientific studies demonstrate

that the presence of defects and damage in existing structures – identified according to the classifications discussed above – significantly increases the sensitivity of strengthening systems to implementation errors [29, 36, 37]. Even when advanced materials are employed, typical shortcomings related to violations of technological regulations, inadequate surface preparation, improper detailing of connections, or neglect of aggressive environmental influences may substantially reduce the effectiveness, durability, and overall reliability of strengthened structures.

Thus, the performance of a strengthening system is governed not only by the selected material or design concept, but also by the interaction between existing defects, damage mechanisms, and the quality of technological execution throughout the strengthening process, which fully corresponds to the life-cycle-oriented and reliability-based approach

adopted in Eurocode and ISO standards [12,14–16, 30-32].

Against this background, the effectiveness of strengthening measures should be considered not only as a result of structural design, but also as a function of how strengthening materials and systems are applied under real conditions of existing defects and damage. The interaction between the initial technical condition of the structure and the technological quality of strengthening works plays a decisive role in the achieved performance of rehabilitation interventions.

Below, the most common cases of improper application of metal-based strengthening elements, high-performance flexible materials (FRP), and connection and anchorage systems are systematized. The analysis focuses on typical technical, technological, and execution-related factors, denoted as F^M , F^F , and F^B , which govern the technical efficiency, reliability, and long-term performance of strengthening systems when applied to existing structures.

Factor F^M covers the specific features of using metal elements (steel, aluminum) applied for structural strengthening. Deficiencies in

material selection, installation technology, corrosion protection, fatigue resistance of connections, as well as insufficient consideration of mechanical loads and geometric characteristics directly affect the reliability and durability of metal-based strengthening solutions [2,18–21].

The combined technical and technological causes of errors related to the use of metal-based strengthening elements can be classified into generalized categories and expressed through the following factor groups:

F_1^M – material and consumable quality;

F_2^M – inadequate environmental / corrosion protection;

F_3^M – inadequate fire/temperature protection;

F_4^M – poor installation and joint quality;

F_5^M – incorrect load mechanics and stress transfer;

F_6^M – geometric and constructive mismatch;

F_7^M – incompatibility of materials;

F_8^M – ignored site/installation constraints.

For each group of influencing factors F^M , corresponding subgroups of technical errors were identified and systematized (Table 1).

Table 1 Typical technical errors and main consequences for metal-based strengthening systems

Табл. 1 Типові технічні помилки та наслідки при використанні підсилювальних елементів з металу

Factor group	Factor subgroup	Typical technical error	Main consequence / risk U
F_1^M	$F_{1,1}^M$	Use of low-quality or non-certified steel	Reduced durability
	$F_{1,2}^M$	Use of poor-quality electrodes or welding consumables	Reduced quality of connections
F_2^M	$F_{2,1}^M$	Installation in saline or humid environments without adequate corrosion protection (primers, coatings, metallization)	Corrosion damage
	$F_{2,2}^M$	Insufficient sealing of joints without considering moisture penetration at the concrete–metal interface	Corrosion of hidden zones
F_3^M	$F_{3,1}^M$	Insufficient or missing fire protection	Loss of load-bearing capacity
	$F_{3,2}^M$	Lack of compensation for thermal deformations and neglect of differences in thermal expansion coefficients of steel and concrete	Additional stresses, debonding, cracking
	$F_{3,3}^M$	Neglecting concrete creep in composite action with steel elements	Loss of contact or local damage

Table 1 (continued)**Табл. 1** (продовження)

F_4^M	$F_{4,1}^M$	Ignoring stress concentration in welded joints under high cyclic loading	Local fatigue damage
	$F_{4,2}^M$	Improper welding and lack of quality control resulting in weld defects (lack of fusion, porosity, slag inclusions)	Formation of fatigue cracks, fatigue failure
F_5^M	$F_{5,1}^M$	Excessive thickness of steel strengthening plates	Local stress concentration, cracking in the base metal
	$F_{5,2}^M$	Rigid fixation of strengthening elements without allowance for deformation	Additional operational stresses
	$F_{5,3}^M$	Insufficient contact quality between steel elements and concrete (absence of anchorage or shear connectors)	Reduced or absent composite action
F_6^M	$F_{6,1}^M$	Installation of straight steel strengthening elements on curved or complex surfaces without pre-forming	Incomplete contact and insufficient force transfer
	$F_{6,2}^M$	Improper placement of strengthening plates on thin-walled elements	Structural failure
	$F_{6,3}^M$	Incorrect positioning of anchors or dowels	Concrete delamination or local failure
F_7^M	$F_{7,1}^M$	Inadequate surface preparation of concrete (cleaning, roughening, use of bonding agents)	Reduced bond strength and durability
	$F_{7,2}^M$	Direct contact of dissimilar metals (e.g., aluminum and steel) without dielectric separation	Galvanic corrosion
F_8^M		Neglect of installation constraints and constructability limitations	Increased risk of defects and reduced performance

Factor F^F reflects the specific characteristics of high-strength flexible materials (FRP), which are associated with relatively high cost, complexity of installation technology, risks of debonding, limited fatigue resistance, and sensitivity to operating conditions such as temperature, humidity, and aggressive environments. Experimental studies have identified several typical debonding zones, including failures within the FRP material, at the adhesive-FRP interface, and at the adhesive-substrate interface (Fig.3) [9]. Improper strengthening of beams or slabs subjected to cyclic loading may lead to progressive delamination or rupture of FRP composites under fatigue effects.

The causes of errors associated with the application of FRP-based strengthening systems can be classified into a set of generalized categories and expressed through the following factor groups [1, 3-7,10, 27, 28]:

- F_1^F - low-quality FRP/adhesives;
- F_2^F - incorrect substrate preparation or poor installation condition;
- F_3^F - mismatch with geometry;

F_4^F - insufficient protection in service.

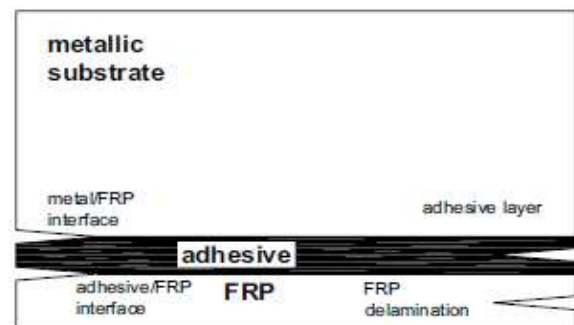


Fig. 3 FRP debonding and failure modes in structural strengthening [9]

Рис. 3 Типи відшарування або руйнування FRP-матеріалу при підсиленні

For each group of influencing factors F^F , corresponding subgroups of technical errors were identified and systematized (Table 2).

Factor F^B encompasses deficiencies related to the use of prefabricated connection and anchorage elements—such as anchors, bolts, and steel plates—taking into account surface

preparation, corrosion protection, installation procedures, operating conditions, and the influence of structural geometry. In many cases, errors at the connection level govern the overall

performance of the strengthening system and may result in loss of composite action or premature failure.

Table 2 Typical technical errors and main consequences for FRP-based strengthening systems

Табл. 2 Типові технічні помилки та наслідки при використанні підсилювальних елементів з FRP

Factor group	Factor subgroup	Typical technical error	Main consequence / risk U
F_1^F	$F_{1,1}^F$	Use of non-certified FRP materials or low-quality adhesives	Loss of bond effectiveness
	$F_{1,2}^F$	Lack of control over adhesive layer thickness	Debonding
F_2^F	$F_{2,1}^F$	Bonding on wet or dusty surfaces	Debonding
	$F_{2,2}^F$	Installation at low temperatures or high humidity	Reduced adhesion
F_3^F	$F_{3,1}^F$	Excessive FRP thickness without structural adaptation	Stress concentration, rupture
	$F_{3,2}^F$	Application of flat FRP systems on curved surfaces	Loss of bond
F_4^F	$F_{4,1}^F$	Absence of fire protection	Loss of strength during fire exposure
	$F_{4,2}^F$	Application of FRP on carbonated concrete	Loss of adhesion, material degradation
	$F_{4,3}^F$	Lack of protection in aggressive environments	Accelerated deterioration
	$F_{4,4}^F$	Neglect of fatigue behavior under cyclic loading	Progressive debonding

Typical technical errors associated with the use of prefabricated connection and anchorage products in structural strengthening can be systematized into several generalized categories and represented by the following groups of factors [9, 11, 22, 24-26]:

F_1^B – violations of installation procedures;

F_2^B – lack of environmental sealing and corrosion protection;

F_3^B – ignored geometry and reinforcement layout.

For each group of influencing factors $F_{k,n}^B$, corresponding subgroups of technical errors were identified and systematized (Table 3).

Table 3 Typical technical errors and main consequences for anchorage and connection systems

Табл. 3 Типові технічні помилки та наслідки при використанні готових з'єднуючих виробів

Factor group	Factor subgroup	Typical technical error	Main consequence / risk U
F_1^B	$F_{1,1}^B$	Installation of anchors without surface cleaning or degreasing	Loss of bond
	$F_{1,2}^B$	Installation on wet surfaces	Loosening or pull-out of connectors
	$F_{1,3}^B$	Use of low-quality or incompatible adhesives	Poor adhesion
	$F_{1,4}^B$	Bolts without pre-tension or improper tightening	Connection loosening

Table 3 (continued)
Табл. 3 (продовження)

	$F_{1,5}^B$	Reuse of bolts	Risk of fatigue failure
	$F_{1,5}^B$	Welding without quality control	Crack initiation zones
F_2^B	$F_{2,1}^B$	Contact of dissimilar metals without insulation	Galvanic corrosion
	$F_{2,2}^B$	Lack of joint sealing	Moisture penetration and corrosion
F_3^F	$F_{3,1}^B$	Installation on thin elements without structural verification	Local crushing, deformation
	$F_{3,2}^B$	Installation on curved surfaces without prior shaping	Incomplete contact
	$F_{3,3}^B$	Installation without considering existing reinforcement	Structural weakening

To link improper-use factors with consequences in a structured way, the typical risk/outcome for a strengthened element is represented as:

$$U_i = f(F_{1,1}^M \dots F_{k,n}^M; F_{1,1}^F \dots F_{k,n}^F; F_{1,1}^B \dots F_{k,n}^B | D_i^R; D_i^K, D_i^C; P_i) \quad (1)$$

where U_i - typical consequence/risk (debonding, corrosion, fatigue cracking, loss of capacity);
 $F_{k,n}^M, F_{k,n}^F, F_{k,n}^B$ - factor subsets describing improper use for metal/FRP/connection products;
 D_i - defect group related to origin (design/manufacture/installation/exploitation);
 D_i^K - defect category (internal/external);
 D_i^C - defect characteristics (visible/hidden; progressive/non-progressive);
 P_i - damage type category (e.g., mechanical/temperature/chemical/explosive).

The overall effectiveness of strengthening under accumulated risks may be expressed as:

$$R = G(U_1, U_2, \dots, U_n) \quad (2)$$

where R - denotes the overall effectiveness,
 U_n - represents a typical risk or consequence.

This function demonstrates the interaction of multiple factors affecting the effectiveness of strengthening materials. Optimization of these parameters provides a basis for improving the quality, structural resilience, and long-term performance of rehabilitated structures.

CONCLUSIONS

1. The study demonstrates that the reduced effectiveness of strengthening interventions in structural rehabilitation is

most often caused by improper application and execution-related factors rather than by inherent limitations of modern strengthening materials or systems.

2. Typical causes of improper use were systematized into three interrelated factor families: metal-based strengthening systems, FRP strengthening systems, and connection and anchorage products. Each family is associated with specific technological vulnerabilities, characteristic failure mechanisms, and potential losses in durability and structural performance.
3. A formalized factor–risk representation was developed to explicitly link improper-use factors with the existing defect and damage context of structures and the resulting performance consequences. This representation provides a consistent basis for quality assurance, risk-oriented assessment, and engineering decision-

making in the design and implementation of strengthening measures.

- The proposed framework is consistent with Eurocode- and ISO-based assessment philosophy and supports a more integrated consideration of material selection, execution quality, and existing structural condition. Its application facilitates the identification of critical weak points in strengthening solutions and contributes to improving the reliability, resilience, and long-term performance of rehabilitated structures.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

LITERATURE

- Руднєва, І., Прядко, Ю., Прядко, М., & Тонкачєв, Г. (2020). Особливості та перспективи використання технологій підсилення будівельних конструкцій композиційними матеріалами при реконструкції споруд. *Будівельні конструкції. Теорія і практика*, (7), 12–22. <https://doi.org/10.32347/2522-4182.7.2020.12-22>
- Zhang, W.H., Lu, D.G., Qin, J., et al. (2021). Value of information analysis in civil and infrastructure engineering: a review. *Journal of Infrastructure Preservation and Resilience*. 2, 16. <https://doi.org/10.1186/s43065-021-00027-0>
- Молодід, О. С., Руднєва, І. М., & Богдан, С. М. (2021). Експериментальне дослідження підсилення металевих конструкцій зовнішнім армуванням методом наклеювання високоміцних композиційних вуглецевих матеріалів (FRP). *Дороги і мости*, (24), 84–96. <https://doi.org/10.36100/dorogimosti2021.24.084>
- Руднєва, І. (2021). Технологічні особливості підсилення металевих конструкцій методом наклеювання високоміцних фіброармованих систем при реконструкції. *Будівельні конструкції. Теорія і практика*, (8), 32–43. <https://doi.org/10.32347/2522-4182.8.2021.32-43>
- Rudnieva, I. N. (2020). Comparative analysis of strengthening of building structures (masonry, metal structures, reinforced concrete) using FRP materials and traditional methods during reconstruction. *Strength of Materials and Theory of Structures*, (105), 267–291. <https://doi.org/10.32347/2410-2547.2020.105.267-291>
- Shaat, A., & Fam, A. (2009). Slender steel columns strengthened using high-modulus CFRP plates for buckling control. *Journal of Composites for Construction*. 13(1), 2–12. [https://doi.org/10.1061/\(ASCE\)1090-0268\(2009\)13:1\(2\)](https://doi.org/10.1061/(ASCE)1090-0268(2009)13:1(2))
- Hollaway, L.C., & Teng, J.G. (2008). Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites. *Cambridge: Woodhead Publishing*. 448 p. ISBN 978-1-84569-448-7.
- Monaldo, E., Nerilli, F., & Vairo, G. (2019). Effectiveness of some technical standards for debonding analysis in FRP-concrete systems. *Composites Part B: Engineering*. 160, 254–267. <https://doi.org/10.1016/j.compositesb.2018.10.022>
- CNR-DT 202/2005. (2007). Guidelines for the design and construction of externally bonded FRP systems for strengthening existing structures. Metallic structures. *Rome: National Research Council (CNR)*, 57 p.
- fib Bulletin No. 14. (2001). Externally bonded FRP reinforcement for RC structures. *Lausanne: International Federation for Structural Concrete (fib)*. 138 p. <https://doi.org/10.35789/fib.BULL.0014>
- fib Bulletin 102. (2023). *Guide for protection and repair of concrete structures*. Lausanne: International Federation for Structural Concrete (fib), 120 p. ISBN 978-2-88394-164-0.
- ДСТУ-Н Б В.1.2-13:2008 (EN 1990:2002, IDN). (2009). Система надійності та безпеки у будівництві. Настанова. Основи проектування конструкцій. Київ: Мінрегіонбуд України 81 с.[Чинний від 2009-07-01]
- ДСТУ – Н Б EN 1991-1-2:2010. (2011). Єврокод 1. Дії на конструкції. Частина 1-2. Загальні дії. Дії на конструкції під час пожежі. Київ: Мінрегіонбуд України 100 с.[Чинний від 2013-07-01]
- ISO 13822:2010. (2010). Bases for design of structures – Assessment of existing structures. *Geneva: International Organization for Standardization*, 44 p. <https://www.iso.org/obp/ui/#iso:std:iso:13822:e-d-2:v1:en>

15. **ISO 2394:2015.** (2015). General principles on reliability for structures. *Geneva: International Organization for Standardization*, 111 p. <https://www.iso.org/obp/ui/#iso:std:iso:2394:ed-4:v1:en>
16. **ISO 15686-3:2002.** (2002). Buildings and constructed assets – Service life planning – Part 3: Performance audits and reviews. *Geneva: International Organization for Standardization*, 29 p. <https://www.iso.org/obp/ui/#iso:std:iso:15686:-3:ed-1:v1:en>
17. **ISO 16311-2:2024.** (2024). Maintenance and repair of concrete structures – Part 2: Assessment of existing concrete structures. *Geneva: International Organization for Standardization.* <https://www.iso.org/obp/ui/#iso:std:iso:16311:-2:ed-2:v1:en>
18. **Барашиков, А.Я., & Малишев О.М.** (2008). Оцінка технічного стану будівель та інженерних споруд: навчальний посібник. Київ, КНУБА, 320 с.
19. **Stewart, M.G., & Mullard, J.A.** (2007). Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures. *Engineering Structures*, 29(7), 1457–1464. <https://doi.org/10.1016/j.engstruct.2006.09.004>
20. **Xia, J., & Jin, W.** (2014). Prediction of corrosion-induced crack width of reinforced concrete structures. *Proceedings of ICDCS 2014*, 146–154. <https://doi.org/10.5703/1288284315395>
21. **Monaldo, E., Nerilli, F., & Vairo, G.** (2019). Effectiveness of some technical standards for debonding analysis in FRP-concrete systems. *Composites Part B: Engineering*, 160, 254–267. <https://doi.org/10.1016/j.compositesb.2018.10.022>
22. **Chen, J. F., & Teng, J. G.** (2003). Shear capacity of FRP-strengthened RC beams: FRP debonding. *Construction and Building Materials*, 17(1), 27–41. [https://doi.org/10.1016/S0950-0618\(02\)00087-0](https://doi.org/10.1016/S0950-0618(02)00087-0)
23. **Cattaneo, S., & Vafa, N.** (2021). Tensile capacity of adhesive anchors in damaged masonry. *Applied Sciences*, 11(21), 10135. <https://doi.org/10.3390/app112110135>
24. **Satoh, T., et al.** (2023). F Analytical study on fracture mechanisms ruling resistant load of post-installed adhesive anchor. *Japan Architectural Review*, 6(1), e12401. <https://doi.org/10.1002/2475-8876.12401>
25. **Tarawneh, A.N., Ross, B.E., & Cousins, T.E.** (2020). Tensile behavior and design of adhesive anchors embedded in thin concrete members. *PCI Journal*, 65(5), 51–64. <https://doi.org/10.15554/pci65.5-03>
26. **Pham, T.M., & Hao, H.** (2016). Review of concrete structures strengthened with FRP against impact loading. *Structures*, 7, 59–70. <https://doi.org/10.1016/j.istruc.2016.05.003>
27. **Büyüköztürk, O., Gunes, O., & Karaca, E.** (2004). Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. *Construction and Building Materials*, 18(1), 9–19. [https://doi.org/10.1016/S0950-0618\(03\)00094-1](https://doi.org/10.1016/S0950-0618(03)00094-1)
28. **Чирва, Т., & Колякова, В.** (2025). Напружено-деформований стан пошкодженого залізничного шляхопроводу та його підсилення вуглепластиковими матеріалами *Опир матеріалів і теорія споруд*, (115), 347–359. <https://doi.org/10.32347/2410-2547.2025.115.347-359>
29. **Biondini, F., & Frangopol, D.M.** (2016). Life-cycle performance of deteriorating structural systems under uncertainty: Review. *Journal of Structural Engineering*, 142(9). [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001544](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001544)
30. **Ang, A. H.-S.** (2011). Life-cycle considerations in risk-informed decisions for design of civil infrastructures. *Structure and Infrastructure Engineering*, 7(1–2), 3–9. <https://doi.org/10.1080/15732471003588239>
31. **Ellingwood, B. R., & Lee, J. Y.** (2016). Life cycle performance goals for civil infrastructure: intergenerational risk-informed decisions. *Structure and Infrastructure Engineering*, 12(7), 822–829. <https://doi.org/10.1080/15732479.2015.1064966>
32. **Ang, A. H.-S., De Leon, D.** (2005). Modeling and analysis of uncertainties for risk-informed decisions in infrastructures engineering. *Structure and Infrastructure Engineering*, 1(1), 19–31. <https://doi.org/10.1080/15732470412331289350>

33. **Прядко, М. В., Руднева, І. М., & Прядко, Ю. М.** (2018). Обстеження та підсилення будівельних конструкцій промислових будівель. Київ: КНУБА, 332 с.
34. **Гладишев, Г., & Гладишев, Д.** (2025). Підходи до оцінки деформацій існуючих будівель щільної забудови на основі результатів обстеження їх фасадів. *Будівельні конструкції. Теорія і практика*, (16), 171–182. <https://doi.org/10.32347/2522-4182.16.2025.171-182>
35. **Клюєв, В., & Бакулін, Є.** (2024). Сучасні методи ідентифікації небезпек руйнування будівель і споруд в реальних умовах експлуатації. *Будівельні конструкції. Теорія і практика*, (15), 86–96. <https://doi.org/10.32347/2522-4182.15.2024.86-96>
36. **Доброхлоп, М., & Доброхлоп, Є.** (2024). Результати технічного обстеження логістичного центру після ракетно-артилерійського впливу. *Будівельні конструкції. Теорія і практика*, (15), 66–74. <https://doi.org/10.32347/2522-4182.15.2024.66-74>
- методом наклеювання високomoditsnykh fibroarmovanykh system pry rekonstruktsii. *Building Constructions. Theory and Practice*, (8), 32–43. [in Ukrainian] <https://doi.org/10.32347/2522-4182.8.2021.32-43>
5. **Rudnieva, I. N.** (2020). Comparative analysis of strengthening of building structures (masonry, metal structures, reinforced concrete) using FRP materials and traditional methods during reconstruction. *Strength of Materials and Theory of Structures*, (105), 267–291. <https://doi.org/10.32347/2410-2547.2020.105.267-291>
6. **Shaah, A., & Fam, A.** (2009). Slender steel columns strengthened using high-modulus CFRP plates for buckling control. *Journal of Composites for Construction*. 13(1), 2–12. [https://doi.org/10.1061/\(ASCE\)1090-0268\(2009\)13:1\(2\)](https://doi.org/10.1061/(ASCE)1090-0268(2009)13:1(2))
7. **Hollaway, L.C., & Teng, J.G.** (2008). Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites. *Cambridge: Woodhead Publishing*. 448 p. ISBN 978-1-84569-448-7.
8. **Monaldo, E., Nerilli, F., & Vairo, G.** (2019). Effectiveness of some technical standards for debonding analysis in FRP-concrete systems. *Composites Part B: Engineering*. 160, 254–267. <https://doi.org/10.1016/j.compositesb.2018.10.022>
9. **CNR-DT 202/2005.** (2007). Guidelines for the design and construction of externally bonded FRP systems for strengthening existing structures. *Metallic structures. Rome: National Research Council (CNR)*, 57 p.
10. **fib Bulletin No. 14.** (2001). Externally bonded FRP reinforcement for RC structures. *Lausanne: International Federation for Structural Concrete (fib)*. 138 p. <https://doi.org/10.35789/fib.BULL.0014>
11. **fib Bulletin 102.** (2023). *Guide for protection and repair of concrete structures*. Lausanne: International Federation for Structural Concrete (fib), 120 p. ISBN 978-2-88394-164-0.
12. **DSTU-N B V.1.2-13:2008 (EN 1990:2002, IDN).** (2009). Systema nadiinosti ta bezpeky u budivnytstvi. Nastanova. *Osnovy proektuvannya konstruktsii*. Kyiv: Minrehionbud Ukrainy. 81 p. [in Ukrainian]
13. **DSTU-N B EN 1991-1-2:2010.** (2011). Eurocode 1. Actions on structures. Part 1-2: Actions on structures exposed to fire. Kyiv: Minrehionbud Ukrainy. 100 p. [in Ukrainian]

REFERENCES

1. **Rudnieva, I., Pryadko, Yu., Pryadko, M., & Tonkacheiev, H.** (2020). Osoblyvosti ta perspektyvy vykorystannia tekhnolohii pidsylennia budivelnykh konstruksii kompozytsiinymy materialamy pry rekonstruktsii sporud. *Building Constructions. Theory and Practice*, (7), 12–22. [in Ukrainian] <https://doi.org/10.32347/2522-4182.7.2020.12-22>
2. **Zhang, W.H., Lu, D.G., Qin, J., et al.** (2021). Value of information analysis in civil and infrastructure engineering: a review. *Journal of Infrastructure Preservation and Resilience*. 2, 16. <https://doi.org/10.1186/s43065-021-00027-0>
3. **Molodid, O. S., Rudnieva, I. M., & Bohdan, S. M.** (2021). Eksperymentalne doslidzhennia pidsylennia metalevykh konstruksii zovnishnim armuvanniam metodom nakleiuвання vysokomoditsnykh kompozytsiinnykh vuhletsevykh materialiv (FRP). *Roads and Bridges*, (24), 84–96. [in Ukrainian] <https://doi.org/10.36100/dorogimosti2021.24.084>
4. **Rudnieva, I.** (2021). Tekhnolohichni osoblyvosti pidsylennia metalevykh konstruksii

14. **ISO 13822:2010.** (2010). Bases for design of structures – Assessment of existing structures. Geneva: International Organization for Standardization, 44 p. <https://www.iso.org/obp/ui/#iso:std:iso:13822:ed-2:v1:en>
15. **ISO 2394:2015.** (2015). General principles on reliability for structures. Geneva: International Organization for Standardization, 111 p. <https://www.iso.org/obp/ui/#iso:std:iso:2394:ed-4:v1:en>
16. **ISO 15686-3:2002.** (2002). Buildings and constructed assets – Service life planning – Part 3: Performance audits and reviews. Geneva: International Organization for Standardization, 29 p. <https://www.iso.org/obp/ui/#iso:std:iso:15686-3:ed-1:v1:en>
17. **ISO 16311-2:2024.** (2024). Maintenance and repair of concrete structures – Part 2: Assessment of existing concrete structures. Geneva: International Organization for Standardization. <https://www.iso.org/obp/ui/#iso:std:iso:16311-2:ed-2:v1:en>
18. **Barashykov, A. Ya., Malyshev, O. M.** (2008). Otsiniuvannia tekhnichnoho stanu budivel ta inzhenernykh sporud: navchalnyi posibnyk. Kyiv, KNUBA, 320 p. [in Ukrainian]
19. **Stewart, M.G., & Mullard, J.A.** (2007). Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures. *Engineering Structures*, 29(7), 1457 – 1464. <https://doi.org/10.1016/j.engstruct.2006.09.004>
20. **Xia, J., & Jin, W.** (2014). Prediction of corrosion-induced crack width of reinforced concrete structures. *Proceedings of ICDCS 2014*, 146–154. <https://doi.org/10.5703/1288284315395>
21. **Monaldo, E., Nerilli, F., & Vairo, G.** (2019). Effectiveness of some technical standards for debonding analysis in FRP-concrete systems. *Composites Part B: Engineering*, 160, 254–267. <https://doi.org/10.1016/j.compositesb.2018.10.022>
22. **Chen, J. F., & Teng, J. G.** (2003). Shear capacity of FRP-strengthened RC beams: FRP debonding. *Construction and Building Materials*, 17(1), 27–41. [https://doi.org/10.1016/S0950-0618\(02\)00087-0](https://doi.org/10.1016/S0950-0618(02)00087-0)
23. **Cattaneo, S., & Vafa, N.** (2021). Tensile capacity of adhesive anchors in damaged masonry. *Applied Sciences*, 11(21), 10135. <https://doi.org/10.3390/app112110135>
24. **Satoh, T., et al.** (2023). F Analytical study on fracture mechanisms ruling resistant load of post-installed adhesive anchor. *Japan Architectural Review*, 6(1), e12401. <https://doi.org/10.1002/2475-8876.12401>
25. **Tarawneh, A.N., Ross, B.E., & Cousins, T.E.** (2020). Tensile behavior and design of adhesive anchors embedded in thin concrete members. *PCI Journal*. 65(5), 51–64. <https://doi.org/10.15554/pci65.5-03>
26. **Pham, T.M., & Hao, H.** (2016). Review of concrete structures strengthened with FRP against impact loading. *Structures*, 7, 59–70. <https://doi.org/10.1016/j.istruc.2016.05.003>
27. **Büyüköztürk, O., Gunes, O., & Karaca, E.** (2004). Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. *Construction and Building Materials*, 18(1), 9–19. [https://doi.org/10.1016/S0950-0618\(03\)00094-1](https://doi.org/10.1016/S0950-0618(03)00094-1)
28. **Chyrva, T., & Koliakova, V.** (2025). Napruzhenno-deformovanyi stan poskodzhenoho zaliznychnoho shliakhoprovodu ta yoho pidsylennia vuhleplastikovymy materialamy. *Strength of Materials and Theory of Structures*, (115), 347–359. [in Ukrainian] <https://doi.org/10.32347/2410-2547.2025.115.347-359>
29. **Biondini, F., & Frangopol, D.M.** (2016). Life-cycle performance of deteriorating structural systems under uncertainty: Review. *Journal of Structural Engineering*, 142(9). [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001544](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001544)
30. **Ang, A. H.-S.** (2011). Life-cycle considerations in risk-informed decisions for design of civil infrastructures. *Structure and Infrastructure Engineering*. 7(1–2), 3–9. <https://doi.org/10.1080/15732471003588239>
31. **Ellingwood, B. R., & Lee, J. Y.** (2016). Life cycle performance goals for civil infrastructure: intergenerational risk-informed decisions. *Structure and Infrastructure Engineering*, 12(7), 822–829. <https://doi.org/10.1080/15732479.2015.1064966>
32. **Ang, A. H.-S., De Leon, D.** (2005). Modeling and analysis of uncertainties for risk-informed

decisions in infrastructures engineering. *Structure and Infrastructure Engineering*, 1(1), 19–31.

<https://doi.org/10.1080/15732470412331289350>

33. Pryadko, M. V., Rudnieva, I. M., & Pryadko, Yu. M. (2018). Obstezhennia ta pidsylennia budivelnykh konstruksii promyslovykh budivel : Navchalnyi posibnyk. Kyiv: KNUBA, 332 p. [in Ukrainian]
34. Hladyshev, H., & Hladyshev, D. (2025). Pidkhydy do otsinky deformatsii isnuiuchykh budivel shchilnoi zabudovy. *Building Constructions. Theory and Practice*, (16), 171–182. [in Ukrainian]
<https://doi.org/10.32347/2522-4182.16.2025.171-182>
35. Klyuev, V., & Bakulin, Ye. (2024). Suchasni metody identyfikatsii nebezpek ruinuvannia budivel. *Building Constructions. Theory and Practice*, (15), 86–96. [in Ukrainian].
<https://doi.org/10.32347/2522-4182.15.2024.86-96>
36. Dobrokhlop, M., & Dobrokhlop, Ye. (2024). Rezultaty tekhnichnoho obstezhennia lohystychnoho tsentru pislia raketno-artyleryiskoho vplyvu. *Building Constructions. Theory and Practice*, (15), 66–74. [in Ukrainian]
<https://doi.org/10.32347/2522-4182.15.2024.66-74>

АНАЛІЗ НЕДОСКОНАЛОГО ЗАСТОСУВАННЯ МАТЕРІАЛІВ ТА СИСТЕМ ПІДСИЛЕННЯ ПРИ РЕКОНСТРУКЦІЇ БУДІВЕЛЬ

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Анотація. Ефективність, надійність і довговічність заходів з підсилення будівельних конструкцій залежать не лише від обраних матеріалів і проектних рішень, а й від якості їх реалізації на всіх етапах процесу реконструкції. Підсилення, як правило, виконується на існуючих конструкціях, які вже містять дефекти та пошкодження, накопичені протягом життєвого циклу, що істотно впливає на перерозподіл напружень, умови зчеплення та довготривалу експлуатаційну придатність. За таких умов навіть сучасні системи підсилення

можуть демонструвати знижену ефективність у разі некоректного врахування проектних припущень, технологічних вимог або впливу експлуатаційного середовища.

У статті проаналізовано типові випадки недосконалого застосування матеріалів і систем підсилення будівельних конструкцій, зокрема традиційних сталевих рішень, систем на основі фіброармованих полімерів (FRP), а також з'єднувальних та анкерних виробів. На основі узагальнення практики технічних обстежень, експериментальних досліджень і нормативно-методичних підходів, узгоджених із принципами Єврокодів та стандартів ISO, систематизовано технічні, технологічні та організаційні помилки, що виникають на етапах проектування, виконання та експлуатації. Особливу увагу приділено взаємозв'язку чинників недосконалого застосування з наявними дефектами та пошкодженнями конструкцій.

Запропоновано узагальнену класифікацію дефектів і пошкоджень як структуровану вхідну інформацію для оцінювання підсилення, що дозволяє аналізувати сценарії недосконалого застосування з урахуванням походження дефектів, їх локалізації, характеру розвитку та впливу на несучу здатність. Розроблено функціонально-структурну модель ризиків, яка формалізує взаємозв'язок між чинниками технічних помилок, характеристиками дефектів і пошкоджень та наслідками для експлуатаційних показників конструкцій. Загальна ефективність підсилення інтерпретується як інтегральна функція накопичених ризиків, пов'язаних із вибором матеріалів, якістю виконання робіт та фактичним технічним станом існуючих конструкцій.

Отримані результати можуть бути використані для вдосконалення процедур контролю якості, зниження технологічних та експлуатаційних ризиків, а також для підтримки ризик-орієнтованого прийняття рішень у процесі реконструкції. Запропонований підхід сприяє підвищенню надійності, стійкості та довготривалої ефективності підсилення конструкцій у межах життєво-циклової концепції.

Ключові слова: підсилення будівельних конструкцій; дефекти; пошкодження; сталеве підсилення; FRP-системи.

Received: February 09, 2026.

Revised: March 03, 2026.

Accepted: May 28, 2026.