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PROPERTIES ON THE BEHAVIOUR OF STEEL-REINFORCED CONCRETE STRUCTURES INFLUENCE OF CONCRETE AND STEEL THERMOPHYSICAL

БЕТОН МЕН БОЛАТТЫҢ ЖЫЛУФИЗИКАЛЫҚ ҚАСИЕТТЕРІНІҢ БОЛАТТЕМІРБЕТОН КОНСТРУКЦИЯЛАРЫНЫҢ ЖҰМЫСЫНА ӘСЕРІ

ВЛИЯНИЕ ТЕПЛОФИЗИЧЕСКИХ СВОЙСТВ БЕТОНА И СТАЛИ НА ПОВЕДЕНИЕ СТАЛЕЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ

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Keywords:
steel–reinforced concrete, thermal actions, thermophysical properties, temperature gradients, thermal stresses, shear connectors, composite interaction, fire exposure.

ABSTRACT

This review-analytical study examines how the thermophysical properties of concrete and steel influence the behavior of steel-reinforced concrete structures under climatic and fire-induced temperature actions. The aim is to systematize the main mechanisms of temperature-induced stresses and deformations and assess their effect on composite action. The methodology includes analysis, classification, comparison, and synthesis of published analytical, experimental, and numerical studies, supported by illustrative calculations of axial stresses, bending moments from temperature gradients, and shear forces in connectors. The results show that differences in thermal expansion, conductivity, and heat capacity generate self-equilibrated stresses, redistribute internal forces, reduce stiffness, and may decrease load-bearing capacity, especially in statically indeterminate systems and under fire. The scientific novelty lies in integrating these mechanisms within a unified interpretation and highlighting the governing role of shear connectors. The findings can support more reliable design models, while further research should refine predictive methods and expand experimental validation.

Түйінді сөздер:
болат–темірбетон, температуралық әсерлер, жылуфизикалық қасиеттер, температуралық градиенттер, температуралық

ТҮЙІНДЕМЕ

Мақалада климаттық және өрт жағдайындағы температуралық әсерлер кезінде бетон мен болаттың жылуфизикалық қасиеттерінің болат-бетон композитті конструкциялардың жұмысына ықпалына шолу-талдамалық талдау жасалған. Зерттеудің мақсаты – температуралық деформациялар мен кернеулердің пайда болу механизмдерін жүйелеу және олардың материалдардың бірлескен жұмысына әсерін бағалау. Әдістеме жарияланған аналитикалық,

кернеулер, ығысу қосқыштары, композиттік өзара әрекет, өрттік әсер.

эксперименттік және сандық зерттеулерді талдау, жіктеу, салыстыру және жинақтауды, сондай-ақ осьтік температуралық кернеулердің, температуралық градиенттерден туындайтын иілу моменттерінің және қосқыштардағы көлденең ығысу күштерінің иллюстрациялық есептерін қамтиды. Сызықтық ұлғаю коэффициенті, жылуөткізгіш-тік және жылусыйымдылық айырмашылықтары өздігінен теңгерілетін кернеулерді, ішкі күштердің қайта бөлінуін, қаттылықтың төмендеуін және көтергіштік қабілеттің азаюын туындататыны анықталды, әсіресе статикалық анықталмаған жүйелерде және өрт кезінде. Зерттеудің ғылыми жаңалығы аталған механизмдерді кешенді жүйелеуде және ығысу қосқыштарының шешуші рөлін негіздеуде. Нәтижелер есептік модельдерді нақтылауға және жобалау сенімділігін арттыруға қолданылуы мүмкін; келешек зерттеулер болжау әдістерін жетілдіруге және эксперименттік валидацияны кеңейтуге бағытталуы тиіс.

Ключевые слова:
сталежелезобетон, температурные воздействия, теплофизические свойства, температурные градиенты, температурные напряжения, сдвиговые соединители, композитное взаимодействие, огневое воздействие.

АННОТАЦИЯ

В статье представлен обзорно-аналитический анализ влияния теплофизических свойств бетона и стали на поведение сталебетонных композитных конструкций при климатических и пожарных температурных воздействиях. Цель исследования состоит в систематизации основных механизмов возникновения температурных деформаций и напряжений и оценке их влияния на совместную работу материалов. Методика включает анализ, классификацию, сопоставление и обобщение опубликованных аналитических, экспериментальных и численных исследований, а также иллюстративные расчёты осевых температурных напряжений, изгибающих моментов от температурных градиентов и поперечных сдвиговых усилий в соединителях. Установлено, что различия в коэффициентах температурного расширения, теплопроводности и теплоёмкости вызывают самоуравновешенные напряжения, перераспределение внутренних усилий, снижение жёсткости и уменьшение несущей способности, особенно в статически неопределимых системах и при пожаре. Научная новизна заключается в комплексной систематизации указанных механизмов и обосновании определяющей роли сдвиговых соединителей. Практическая значимость результатов связана с уточнением расчётных моделей и повышением надёжности проектирования; дальнейшие исследования должны быть направлены на совершенствование прогнозных методов и экспериментальную верификацию.

INTRODUCTION

Steel-reinforced concrete structures are currently widely used in civil and industrial construction due to the rational combination of the strength and deformation properties of steel and concrete. The composite action of these materials makes it possible to efficiently resist both permanent and variable loads, ensuring high load-bearing capacity, stiffness, and economic efficiency of structural solutions. At the same time, the reliability and durability of steel-reinforced concrete elements are largely governed by their service conditions, including the effects of temperature actions.

Unlike conventional design loads, temperature actions are complex in nature and often non-uniform. They manifest themselves in the form of daily and seasonal climatic fluctuations, temperature gradients across the cross-section of elements, as well as extreme thermal effects arising during fire exposure. Significant differences in the thermophysical properties of concrete and steel, such as the coefficients of linear thermal expansion, thermal conductivity, and heat capacity, lead to dissimilar material responses to temperature changes. Under composite action, this results in the development of self-equilibrated internal stresses, additional axial forces, bending moments, and increased shear stresses in the steel-concrete interface zone.

Temperature effects play a particularly important role in statically indeterminate systems and in structures operating under continental climate conditions characterized by substantial annual temperature variations. In such environments, temperature-induced forces may reach magnitudes comparable to those caused by service loads and can significantly affect the stress–strain state of elements, the performance of shear connectors, and the overall structural stability. Under fire exposure, thermal effects are further intensified by the degradation of strength and deformation properties of materials, which may lead to disruption of composite action and redistribution of internal forces.

Despite the existence of design codes regulating the calculation of steel-reinforced concrete structures with allowance for temperature actions, practical assessments are often limited to simplified approaches. This highlights the need for a more detailed analysis of the thermophysical properties of concrete and steel and their influence on the behavior of composite elements under various thermal regimes.

This article examines the principal mechanisms governing the formation of temperature-induced deformations and stresses in steel-reinforced concrete structures. The effects of temperature gradients across the cross-section, climatic and fire actions are analyzed, and the role of shear connectors in ensuring composite action is assessed. The obtained results contribute to a deeper understanding of the thermal behavior of steel-reinforced concrete elements and may be applied in the analysis and design of structures operating under complex climatic and service conditions.

LITERATURE REVIEW

The development of steel-reinforced concrete (SRC) structures is associated with their high load-bearing capacity, rational use of materials, and efficient composite interaction between steel and concrete in buildings and structures of various functional purposes. Along with service loads, temperature actions have a significant influence on the stress–strain state of such structures and may be climatic, technological, or accidental in nature. Under continental climate conditions characterized by large daily and seasonal temperature variations, the consideration of thermal effects becomes particularly important (Bai et al., 2023; Zhang et al., 2024; Zhou et al., 2020; Huang et al., 2023).

Recent studies indicate that a key feature of the behavior of steel-reinforced concrete structures under temperature actions is the difference in the thermophysical properties of steel and concrete, primarily the coefficients of linear thermal expansion, thermal conductivity, and heat capacity. These differences lead to non-uniform temperature-induced deformations and the formation of additional internal forces in composite elements even in the absence of external loading (Zhang et al., 2020; Fan et al., 2022; Zhu et al., 2020; Zhou et al., 2020).

It has been established that the magnitude of temperature deformations in concrete significantly depends on its moisture content, age, type of aggregates, and heat-transfer conditions, which further complicates the composite interaction of materials within SRC cross-sections. When a rigid connection exists between the steel and concrete components, free thermal expansion is restrained, resulting in the development of self-equilibrated axial stresses that are redistributed between the components of the composite element (Li et al., 2021; Zhang et al., 2022; Mansour & Ebid, 2023).

A separate line of research focuses on the influence of temperature gradients across the depth of steel-reinforced concrete elements. Under real service conditions, temperature distribution over the cross-section is non-uniform due to solar radiation, heat transfer through enclosing structures, and the thermal inertia of concrete components. Studies conducted on steel-reinforced concrete and related composite structures demonstrate that temperature gradients can generate bending moments comparable in magnitude to those induced by service loads (Zhang et al., 2023; Bai et al., 2023; Huang et al., 2023; Zhou et al., 2020).

Similar conclusions have been reported in a number of studies, which emphasize that temperature-induced bending moments are of an inherent nature and may arise even in the absence of external loads. In statically indeterminate systems, such deformations are partially or fully restrained, which can lead to an increase in internal forces and additional loading of connecting elements (Zhang et al., 2020; Zhang et al., 2022).

The scientific literature also highlights that climatic temperature variations cause cyclic loading of steel-reinforced concrete structures. Daily and seasonal temperature changes result in repeated cycles of tension and compression, which are particularly critical for the steel–concrete interface. Recent studies show that repeated thermal cycles contribute to the accumulation of damage in concrete, the development of microcracks, and the degradation of bond between concrete, reinforcement, and shear connectors (Sheng et al., 2020; Zhu et al., 2020; Yang, B. et al., 2023).

It is noted that shear connectors, which transfer shear forces caused by relative longitudinal slip between steel and concrete, are the most sensitive to temperature cycling. During long-term service, this may lead to fatigue-related reduction in connector strength and a decrease in the stiffness of the composite cross-section, which should be taken into account in the design and durability assessment of SRC structures (Mansilla et al., 2024; Maliji & Yousefpour, 2023; Ding et al., 2025).

A substantial body of research is devoted to the analysis of steel-reinforced concrete structures under fire exposure. It has been established that at temperatures of approximately 500–600 °C, the strength and deformation properties of steel decrease sharply, whereas concrete, due to its higher thermal inertia, retains its load-bearing capacity for a longer time (Bolina et al., 2021; Ding et al., 2023; Peng & Zhou, 2023; Liu et al., 2022).

At temperatures exceeding 700–800 °C, dehydration and spalling processes occur in concrete, leading to the loss of the protective cover and accelerated heating of steel elements. Under such conditions, the load on shear connectors increases significantly, and degradation of bond may result in the loss of composite action and the transition of the element to a non-composite behavior mode (Drury & Quiel, 2023; Yang, W. et al., 2023; Martinez & Jeffers, 2021a; Li et al., 2023; Zhang et al., 2025; Long et al., 2024; Wang et al., 2025).

Experimental and numerical studies reported in the literature indicate that exposure to high temperatures leads to a complex degradation of the mechanical properties of steel and concrete, accompanied by stiffness reduction, possible growth of internal forces, and deterioration of the performance of the steel–concrete connection zone. The relevance of performance-based approaches to fire analysis of composite systems is also emphasized in recent studies (Bolina et al., 2021; Ding et al., 2023; Martinez & Jeffers, 2021a; Gernay & Elhami Khorasani, 2020).

The conducted review of scientific sources shows that temperature actions are considered in contemporary research as one of the significant factors affecting the behavior of steel-reinforced concrete structures. Differences in the thermophysical properties of steel and concrete, the presence of temperature gradients, climatic fluctuations, and fire exposure generate additional internal forces that, in some cases, can make a noticeable contribution to the overall stress–strain state of elements (Zhang et al., 2020; Bai et al., 2023; Zhu et al., 2020).

The results of recent studies point to the necessity of a comprehensive consideration of temperature effects in the design and analysis of SRC structures, especially for regions with continental climates. This determines the relevance of further research aimed at refining calculation models and developing effective structural solutions that ensure the reliability and durability of steel-reinforced concrete systems.

MATERIALS AND METHODS

The present study is conducted as an analytical and theoretical investigation aimed at the systematization and generalization of contemporary scientific approaches to the assessment of temperature actions on steel-reinforced concrete structures. The methodological framework of the research is based on an integrated approach that includes the analysis of published scientific studies, synthesis of experimental and numerical research results, and comparison of various models used to describe temperature-induced stress–strain behavior of composite elements.

The research materials consist of peer-reviewed scientific publications by domestic and international authors devoted to the analysis of temperature deformations, thermal stresses, and the features of composite interaction between steel and concrete under climatic and fire exposure. A significant portion of the reviewed sources addresses the modeling of non-uniform temperature fields and temperature gradients in composite elements (Zhang et al., 2020; Zhu et al., 2020; Fan et al., 2022; Bai et al., 2023; Zhou et al., 2020; Huang et al., 2023), as well as studies devoted to heat-transfer processes in concrete components and related structural systems (Mansour & Ebid, 2023).

The research methodology is based on the analysis and systematization of up-to-date scientific data presented in publications focused on temperature effects on steel-reinforced concrete structures. Within the scope of this study, investigations addressing both short-term and long-term temperature actions were reviewed, including daily and seasonal climatic variations, as well as extreme thermal regimes arising during fire exposure (Bolina et al., 2021; Martinez & Jeffers, 2021a; Martinez & Jeffers, 2021b; Ding et al., 2023; Drury & Quiel, 2023; Peng & Zhou, 2023).

The methodology of the study is founded on the following methods:

1. Scientific publications were classified according to thematic criteria reflecting key aspects of temperature effects on steel-reinforced concrete structures. Particular attention was paid to studies devoted to the thermophysical properties of steel and concrete, the formation of temperature gradients across element cross-sections, the influence of climatic temperature variations, and the behavior of steel-reinforced concrete structures and shear connectors under fire and elevated temperature exposure. This grouping enabled comparison of different scientific approaches and identification of common patterns in the development of temperature-induced deformations and internal forces in composite elements.

2. A comparative method was used to examine different approaches to the evaluation of temperature-induced deformations and stresses in steel-reinforced concrete elements. This analysis made it possible to identify both common trends and discrepancies in the interpretation of thermal effects, as well as to determine areas where a unified methodological framework has not yet been established.

3. The provisions of current design codes related to the consideration of temperature actions in the analysis of steel-reinforced concrete structures were examined. Special attention was given to comparing regulatory requirements with the conclusions of scientific studies, which allowed potential limitations and assumptions inherent in normative calculation methods to be identified.

4. Based on published data, the results of experimental testing and numerical simulations addressing the influence of temperature on the mechanical properties of steel, concrete, and connecting elements were summarized. This made it possible to develop an integrated understanding of the changes in the stress–strain state of steel-reinforced concrete structures under various temperature regimes.

The study was carried out in several successive stages.

At the first stage, a collection and preliminary analysis of scientific and regulatory sources addressing temperature actions on steel-reinforced concrete structures was performed. The selected sources were evaluated in terms of scientific relevance, completeness of the presented data, and applicability to contemporary design conditions.

At the second stage, a critical assessment of the selected materials was conducted. Particular attention was paid to the analysis of the adopted calculation models, experimental assumptions and simplifications, as well as the extent to which real service conditions of structures were taken into account.

At the third stage, the obtained data were systematized and the main patterns governing the influence of temperature actions on the behavior of steel-reinforced concrete elements were identified. Based on a comparative analysis, the key factors determining the development of temperature-induced stresses and deformations were distinguished.

The final stage of the study was aimed at formulating generalized conclusions that may be used as a theoretical basis for further analytical, experimental, and design-oriented research on steel-reinforced concrete structures.

It should be noted that the study has a review and analytical character and is based on published data. The absence of original experimental testing and numerical modeling limits the possibility of quantitative assessment of certain parameters. Nevertheless, the performed analysis makes it possible to develop an integrated understanding of the current state of research in this field and to identify promising directions for further scientific investigations.

Steel and concrete are characterized by significantly different thermophysical properties, which determine their dissimilar response to temperature variations and, consequently, have a pronounced influence on the conditions of composite interaction within steel-reinforced concrete structures. One of the key parameters governing the thermal sensitivity of a material is the coefficient of linear thermal expansion. For steel, its value is approximately $\alpha_c \approx 12 \cdot 10^{-6} 1/^\circ\mathrm{C}$, whereas for concrete it typically lies within the range $\alpha_c \approx 8 - 11 \cdot 10^{-6} 1/^\circ\mathrm{C}$ and depends on the type of concrete, its density, moisture content, and age. This variability is confirmed by the results of experimental and numerical studies (Zhang et al., 2020; Bai et al., 2023). A comparison of the above values is presented in Figure 1.

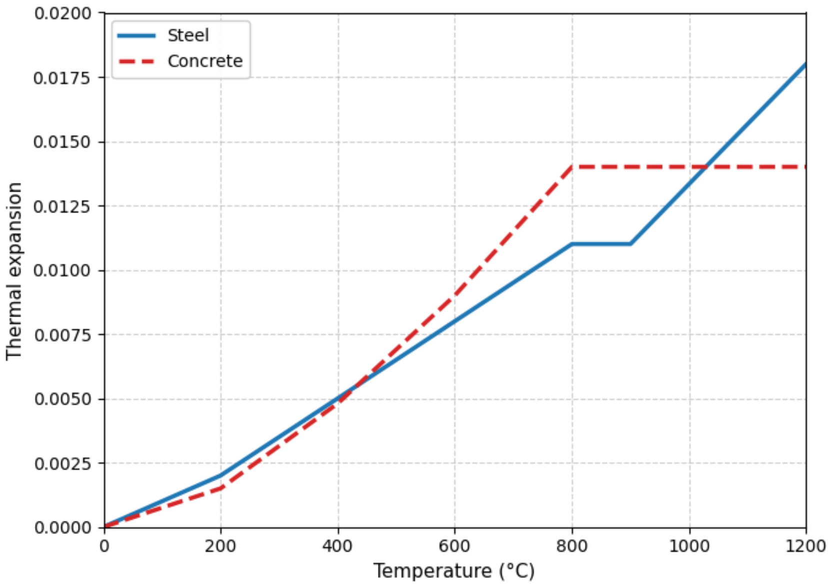

Figure 1. Thermal expansion of steel and concrete at different temperatures

Note – compiled by the authors

Thus, the difference between the coefficients of linear thermal expansion of steel and concrete reaches 20–35%, which leads to the development of non-uniform temperature-induced deformations within the composite cross-section (Zhang et al., 2020; Bai et al., 2023). With increasing temperature, the steel component of an element tends to expand more intensively than the concrete component, as confirmed by numerical and experimental studies on the temperature-induced stress state of steel-reinforced concrete elements (Fan et al., 2022; Zhu et al., 2020). However, composite action within an SRC element restrains the free deformation of each material, resulting in the generation of additional internal stresses in the cross-section.

These stresses are primarily manifested in the form of axial forces arising from the difference in thermal elongation between steel and concrete and from the restraint provided by the intermaterial connections. At the same time, the stress level in the zone of shear connectors increases, as these elements ensure composite action by preventing relative longitudinal slip between the steel and concrete components (Zhang et al., 2022; Fan et al., 2022). In the presence of significant temperature gradients, the load acting on the connecting elements may reach magnitudes comparable to those induced by service loads, as reported in studies devoted to the analysis of temperature fields and internal forces in composite cross-sections (Bai et al., 2023).

In addition to axial forces, transverse shear stresses also develop within the composite cross-section, being particularly pronounced in regions of connector concentration and in transitional zones of the section. As demonstrated in a number of studies, the presence of such stresses may lead to redistribution of internal forces within the slab structure, reduction in connection stiffness, and increased sensitivity of steel-reinforced concrete structures to cyclic and fatigue-related actions (Sheng et al., 2020; Zhu et al., 2020; Mansilla et al., 2024).

RESULTS AND DISCUSSION

Under real service conditions, steel-reinforced concrete structures almost never operate under a uniform temperature field across the cross-section. As a rule, temperature varies along the depth of the element, forming a temperature gradient, the presence of which leads to the development of additional deformations and internal forces that are not directly associated with external loading but have a significant influence on the stress–strain state of the structure (Zhang et al., 2020; Bai et al., 2023). Typical examples of temperature gradient distributions across the cross-section are shown in Figure 2.

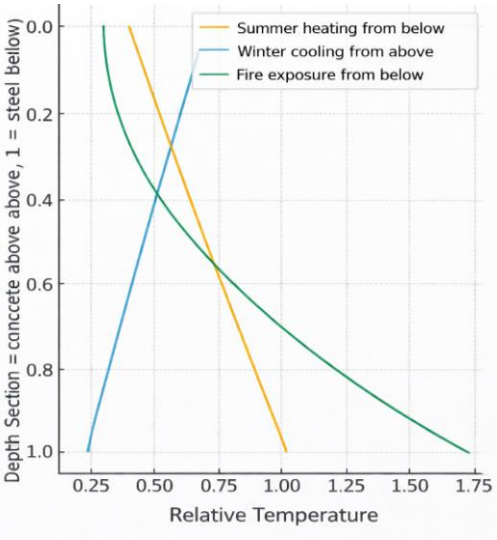

Figure 2. Temperature gradient distributions across the cross-section

Note – compiled by the authors

The nature of temperature distribution in steel-reinforced concrete elements is governed by the type of thermal action and the adopted structural configuration. For composite floors on profiled steel decking located directly beneath the roof, a typical situation arises in which solar radiation has a more pronounced effect on the lower steel component. Due to its lower heat capacity and higher thermal conductivity, the profiled steel deck heats up more rapidly and reaches higher temperatures than the upper concrete slab. As a result, the lower part of the cross-section becomes warmer than the upper part, leading to curvature of the element and the development of additional temperature-induced bending moments. In terms of deformation pattern, these moments are equivalent to those caused by service loads producing downward deflection.

During the winter period, the temperature field may exhibit the opposite character. Under low ambient temperatures, the concrete part of the floor—especially in unheated or poorly insulated areas—may cool more intensively, whereas steel elements located closer to the heated interior volume of the building or protected by finishing layers can retain a higher temperature. In this case, a temperature gradient is formed in which the upper zone of the cross-section is colder than the lower zone. Such a temperature distribution also induces curvature of the element, but with the opposite direction of curvature, resulting in bending moments that differ in both sign and magnitude from those caused by service loads (Zhang et al., 2020; Bai et al., 2023).

The most unfavorable conditions occur under fire exposure, for example when a fire develops beneath the structure. The lower part of a steel beam or profiled deck is heated much more rapidly and to significantly higher temperatures than the upper concrete slab. Under these conditions, steel experiences a substantial reduction in elastic modulus and yield strength, while the temperature gradient across the cross-section becomes extremely steep. As a consequence, considerable temperature-induced bending moments and axial forces are generated, which in some adverse scenarios may reach or even exceed the levels associated with service load effects. At the same time, the composite action of the element is disrupted, and the connecting devices operate in a state close to their ultimate capacity (Bolina et al., 2021; Ding et al., 2023).

It is important to emphasize that temperature gradients give rise to so-called self-equilibrated (inherent) stresses. Even in the absence of external loading, a composite cross-section tends to bend due to non-uniform thermal deformations. In statically indeterminate systems, such curvature is partially or fully restrained by boundary and support conditions, resulting in the development of additional internal forces. When combined with service loads, these forces may lead to redistribution of bending moments, increased stress levels in specific zones of the cross-section, and a reduction in the available load-bearing capacity.

For steel-reinforced concrete structures, particularly those operating under continental climate conditions characterized by large daily and seasonal temperature variations, the consideration of temperature gradients across the cross-section is an essential aspect of structural analysis and reliability assessment. During design, it is necessary to account for possible types of temperature fields and their interaction with service loads, which enables an accurate evaluation of the stress–strain state of composite elements and ensures the required level of safety and durability.

Climatic factors

Climatic temperature actions are among the most significant factors governing the behavior of steel-reinforced concrete structures. Under continental climate conditions, daily temperature fluctuations may reach 20–30 °C, while seasonal variations can amount to 50–65 °C, resulting in regular cycles of heating and cooling of structural elements. The most intensive heating is typically experienced by metallic components of floors and roofs exposed to solar radiation; in some cases, the temperature of profiled steel decking or the bottom flanges of steel beams may reach 70–85 °C, which is consistent with studies on solar-radiation-induced temperature fields and non-uniform heating of structural members (Huang et al., 2023; Zhou et al., 2020).

Due to the differences in the thermophysical properties of materials, a pronounced temperature gradient develops within the composite cross-section, as steel heats up more rapidly and to higher temperatures than the concrete component. This behavior is confirmed by field observations and analytical studies (Zhu et al., 2020; Huang et al., 2023). A typical temperature distribution across the cross-section is shown in Figure 3.

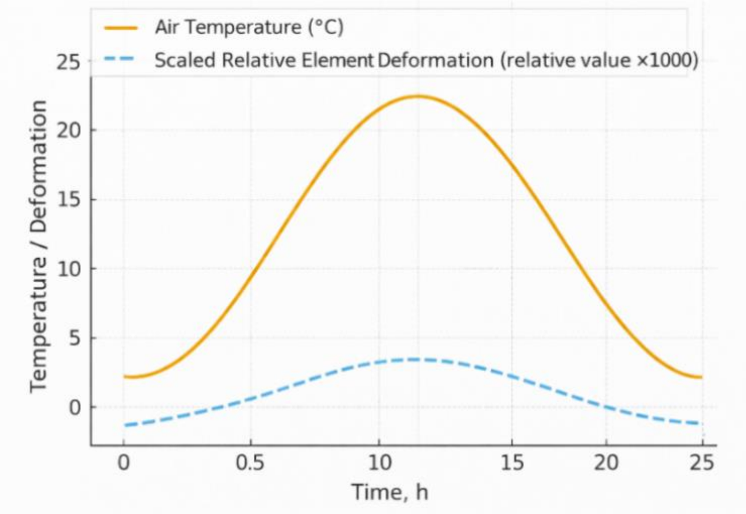

Figure 3. Daily temperature fluctuations and schematic deformation of a steel-concrete composite member

Note – compiled by the authors

Due to the differences in the thermophysical properties of materials, a pronounced temperature gradient develops within the composite cross-section, as steel heats up more rapidly and to higher temperatures than the concrete component. This behavior is confirmed by field observations and analytical studies (Zhu et al., 2020). A typical temperature distribution across the cross-section is shown in Figure 3.

Differences in the temperature-induced deformations of steel and concrete lead to periodic tensile and compressive actions in steel-reinforced concrete systems under cyclic climatic temperature variations. The zones most sensitive to such effects are the material interface regions, where shear connectors are subjected to repeated shear forces caused by relative longitudinal slip between the steel and concrete components. These cyclic actions may accumulate over time, promoting the development of fatigue damage, a reduction in the strength of connecting elements, degradation of bond in the steel–concrete interface, and the formation of microcracks in the concrete slab, as reported in recent studies on the thermal stress behavior of composite structures (Zhu et al., 2020; Yang, B. et al., 2023).

In the long term, the progression of these processes may result in a reduction in the stiffness of the composite cross-section and deterioration of its load-bearing capacity. Therefore, climatic temperature variations should be regarded as an important design factor governing the deformation behavior of steel-reinforced concrete structures, affecting the durability of shear connectors, and requiring mandatory consideration in design and reliability assessment of SRC systems.

Fire exposure

Fire exposure causes extremely intense and non-uniform heating of steel-reinforced concrete structural elements, leading to significant changes in their mechanical properties and disruption of the composite interaction between steel and concrete. Due to its high thermal conductivity, steel heats up much faster than the concrete component, and already at temperatures of approximately 500–600 °C its strength and elastic modulus decrease by about half. This is accompanied by an increase in thermal deformations, a reduction in the load-bearing capacity of the element, and an elevated risk of local instability, as confirmed by experimental and numerical studies on the fire performance of composite structures (Bolina et al., 2021; Ding et al., 2023; Peng & Zhou, 2023; Liu et al., 2022).

Concrete is characterized by higher thermal inertia and, at the initial stage of a fire, retains its load-bearing capacity for a longer period. However, at temperatures on the order of 700–900 °C, processes of dehydration, thermal expansion of aggregates, and accumulation of internal pore pressures develop within the concrete matrix, resulting in intensive cracking and spalling phenomena. The loss of the protective concrete cover significantly accelerates the heating of steel elements and shear connectors, further aggravating the disruption of composite action and contributing to a rapid reduction in the fire resistance of the structure (Martinez & Jeffers, 2021b; Li et al., 2023; Zhang et al., 2025; Long et al., 2024; Wang et al., 2025). Typical forms of concrete damage under high-temperature exposure are shown in Figure 4.

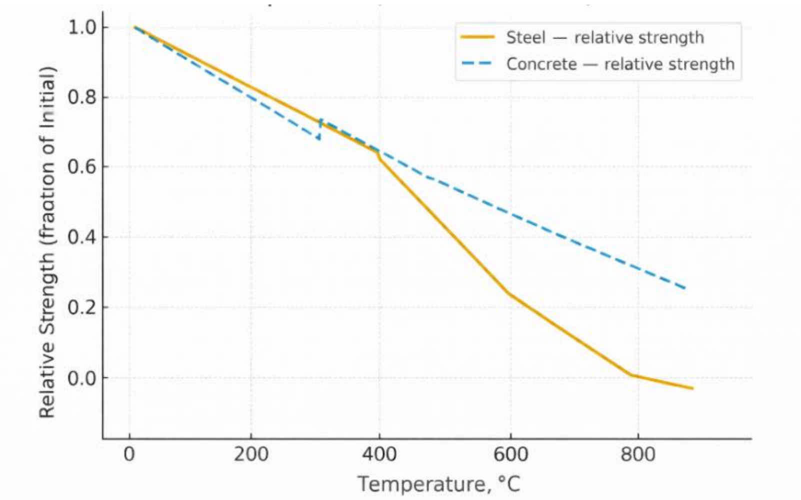

Figure 4. Strength degradation of steel and concrete with increasing temperature

Note – compiled by the authors

A pronounced temperature gradient across the cross-section—resulting from rapid heating of the lower steel component and slower heating of the concrete—leads to curvature of the element and the development of additional bending moments, which often exceed those caused by service loads. In statically indeterminate systems, this effect gives rise to significant self-equilibrated thermal stresses and contributes to an accelerated reduction in load-bearing capacity. Similar tendencies are also reported for localized and natural fire scenarios in restrained composite systems (Drury & Quiel, 2023; Peng & Zhou, 2023).

At the same time, the results of recent experimental and numerical studies indicate that the fundamental mechanisms of composite interaction between steel and concrete remain of decisive importance when analyzing the behavior of steel-reinforced concrete structures under fire conditions. Even under substantial degradation of the mechanical properties of materials, temperature-induced deformations, interaction at the steel–concrete interface, and the performance of shear connectors continue to play a governing role in determining the load-bearing capacity and stability of composite elements (Bolina et al., 2021; Martinez & Jeffers, 2021a; Ding et al., 2023; Yang, W. et al., 2023). These findings are in agreement with contemporary performance-based approaches to the fire design of composite structures (Gernay & Elhami Khorasani, 2020).

Temperature-induced stresses and their influence on SRC elements

Axial temperature-induced stresses arise in steel-reinforced concrete structures when free thermal expansion or contraction of an element is restrained by supports, rigid connections, or monolithic segments. Because steel has a higher coefficient of linear thermal expansion than concrete, composite action under temperature changes leads to the development of internal forces: the steel component tends to expand to a greater extent, while the concrete restrains this deformation. As a result, axial temperature stresses of opposite sign are formed within the components of the composite cross-section, as reported in studies on the thermal stress behavior of steel-reinforced concrete elements (Zhang et al., 2020; Bai et al., 2023).

In statically indeterminate systems, such stresses may reach significant magnitudes, since the structure has limited ability to accommodate thermal actions through changes in shape or redistribution of deformations. Under these conditions, axial temperature-induced forces become one of the governing factors in structural analysis, exerting a substantial influence on the distribution of internal forces and potentially reducing the available load-bearing capacity. The consideration of axial temperature stresses is particularly important under large temperature variations and in cases of non-uniform heating along the length of an element, as confirmed by numerical and analytical studies of composite systems (Fan et al., 2022).

The calculation of temperature-induced deformations and the corresponding axial stresses in the present study was performed under the assumption of full composite action between steel and concrete, with no slip at the interface, equality of longitudinal strains of the composite cross-section components, and the absence of external axial force. The temperature field along the length of the element was assumed to be uniform, and the material behavior was considered within the elastic deformation range. These assumptions are consistent with those commonly adopted in scientific studies addressing temperature-induced internal forces in steel-reinforced concrete structures (Zhu et al., 2020).

For the calculation, the following data were adopted:

Coefficients of linear thermal expansion:

- steel – $\alpha_s = 12 \cdot 10^{-6} 1/°\mathrm{C}$;
- concrete – $\alpha_c = 10 \cdot 10^{-6} 1/°\mathrm{C}$.

Elastic moduli:

- steel – $E_s = 200000$ MPa;
- concrete – $E_c = 30000$ MPa.

Relative cross-sectional areas:

- steel – $A_s = 0{,}1$;
- concrete – $A_c = 0{,}9$.

Temperature variation range:

- $\Delta T = -40 \ldots +60°C$

The free thermal strains of steel and concrete are determined according to:

$$\varepsilon_{free} = \alpha \cdot \Delta T \tag{1}$$

Accordingly, the following expressions are obtained:

-for steel – $\varepsilon_{free} = \alpha_s \cdot \Delta T$

-for concrete – $\varepsilon_{free} = \alpha_c \cdot \Delta T$

The difference in free thermal strains is defined as:

$$\Delta\varepsilon_{free} = \varepsilon_{s,free} - \varepsilon_{c,free} \tag{2}$$

Due to full composite action, the actual longitudinal strain of the element is identical for steel and concrete: $\varepsilon_s = \varepsilon_c = \varepsilon$.

In the absence of an external axial force, the equilibrium condition is expressed as:

$$N_s + N_c = 0 \tag{3}$$

where the axial forces in the materials are defined as:

$$N_s = \sigma_s \cdot A_s, N_c = \sigma_c \cdot A_c \tag{4}$$

The stress–strain relationships are written as:

$$\sigma_s = E_s(\varepsilon - \varepsilon_{s,free}), \sigma_c = E_c(\varepsilon - \varepsilon_{c,free}) \tag{5}$$

Substitution into the equilibrium equation yields the expression for the common longitudinal strain of the composite cross-section:

$$\varepsilon = \frac{A_s \cdot E_s \cdot \varepsilon_{s,free} + A_c \cdot E_c \cdot \varepsilon_{c,free}}{A_s \cdot E_s + A_c \cdot E_c} \tag{6}$$

After determining ε the temperature-induced stresses in steel and concrete are calculated using the above expressions.

The results of the calculation of free thermal strains and self-equilibrated temperature stresses are presented in Table 1.

Table 1. Modeling of axial temperature-induced deformations and stresses

$\Delta T\ (°C)$	$\Delta\varepsilon_{sfree}\ (\times 10^{-5})$	$\Delta\varepsilon_{cfree}\ (\times 10^{-5})$	$\Delta\varepsilon_{free}\ (\times 10^{-5})$	$\sigma_s\ (MPa)$	$\sigma_c\ (MPa)$
-40	-48.0	-40.0	-8.0	9.19	-1.02
-20	-24.0	-20.0	-4.0	4.6	-0.51
0	0.0	0.0	0.0	0.0	0.0
+20	+24.0	+20.0	+4.0	-4.6	0.51
+40	+48.0	+40.0	+8.0	-9.19	1.02
+60	+72.0	+60.0	+12.0	-13.79	1.53
Note – compiled by the authors					

The presented results indicate that, in the presence of a nonzero difference between the coefficients of thermal expansion of steel and concrete, self-equilibrated temperature-induced stresses develop under conditions of composite action. The magnitude of these stresses increases proportionally with the temperature change. During heating, compressive stresses are generated in the steel component, while tensile stresses develop in the concrete; during cooling, the stress pattern is reversed.

The obtained values demonstrate that, within the adopted assumptions and calculation framework, temperature-induced stresses may reach engineering-significant levels comparable to those caused by service loads. This observation is consistent with the findings of numerous analytical and numerical studies and indicates that such stresses should be explicitly considered in the analysis and design of steel-reinforced concrete elements.

Bending moments induced by temperature gradients

Temperature gradients across the depth of a steel-reinforced concrete element lead to non-uniform deformations of the steel and concrete components of the cross-section. When the lower zone is heated more intensively than the upper zone (or under the reverse temperature distribution), curvature of the element occurs, which in its mechanical nature is analogous to the action of a distributed load. As a result of such a non-uniform temperature field, inherent bending moments develop within the composite cross-section. These moments arise even in the absence of external forces and govern an additional stress state of the structure, as confirmed by analytical and numerical studies on temperature-induced bending of steel-reinforced concrete elements (Zhang et al., 2020).

A steel-reinforced concrete element with full composite action between steel and concrete (composite cross-section) is considered.

The coefficients of linear thermal expansion are assumed as follows:

- steel - $\alpha_s = 12 \cdot 10^{-6} 1/°C$;
- concrete - $\alpha_c = 10 \cdot 10^{-6} 1/°C$

The difference between the coefficients is:

$$\Delta\alpha = \alpha_s - \alpha_c = 2 \cdot 10^{-6} 1/°C$$

The effective lever arm between the “characteristic” fibers of steel and concrete (conventionally taken as the distance between the centroids of deformation) is assumed as: $h_0 = 0{,}3m$

The effective bending stiffness of the composite element is taken as:

$$(EI)_{eff} = 1{,}35 \cdot 10^8 N \cdot m^2$$

A temperature gradient across the depth of the cross-section, ΔT, induces different thermal deformations in the steel and concrete components.

The cross-sectional temperature gradient scheme (gradient along the depth) is defined as follows:

- upper zone temperature: T_{top}
- lower zone temperature: T_{bot}

The temperature gradient is expressed as:

$$\Delta T = T_{bot} - T_{top} \quad (7)$$

When the lower zone is warmer than the upper one, the element tends to bend downward (Figure 5).

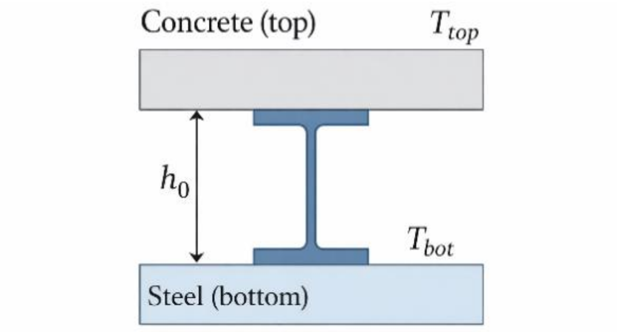

Figure 5. Calculation scheme of the temperature gradient across the depth of a steel-reinforced concrete cross-section

Note – compiled by the authors

Determination of the difference in thermal strains

Thermal strain of a material:

$$\varepsilon_T = \alpha \cdot \Delta T \quad (8)$$

Difference between the thermal strains of steel and concrete:

$$\Delta\varepsilon = (\alpha_s - \alpha_c) \cdot \Delta T = \Delta\alpha \cdot \Delta T \quad (9)$$

If steel and concrete are connected (i.e., the shear connectors are effective), forced compatibility of deformations arises, which manifests itself in the form of curvature:

$$\kappa_T = \frac{\Delta\varepsilon}{h_0} = \frac{(\alpha_s - \alpha_c) \cdot \Delta T}{h_0} \quad (10)$$

A notional temperature-induced moment is introduced as a moment that produces the same curvature in the composite element:

$$M_T = (EI)_{eff} \cdot \kappa_T \quad (11)$$

By substituting the expressions, the following relation is obtained:

$$M_T = (EI)_{eff} \cdot \frac{\Delta\alpha \cdot \Delta T}{h_0} \tag{12}$$

Final convenient formula:

$$M_T = 0{,}9 \cdot \Delta T(°C), \Delta\varepsilon = 2 \times 10^{-6} \cdot \Delta T \tag{13}$$

The calculation results are presented in Table 2.

Table 2. Example of temperature-induced bending moments for a cross-sectional temperature gradient ΔT

ΔT across the cross-section ($°C$)	Difference in thermal strains (×10^{-5})	Notional bending moment (M_T) ($kN \cdot m$)	Deformation pattern
10	2.0	9	lower zone warmer
20	4.0	18	pronounced curvature
30	6.0	27	noticeable moments at supports
40	8.0	36	moments comparable to service loads
60	12.0	54	critical level
Note – compiled by the authors			

The analysis of the calculation results presented in Table 2 shows that an increase in the temperature gradient across the depth of a steel-reinforced concrete cross-section leads to an almost linear growth of the difference in thermal strains and, as a consequence, to an increase in the notional temperature-induced bending moments. Even at temperature gradient values of about $\Delta T = 20 - 30\ °C$ temperature-induced moments are formed whose magnitudes become comparable to those caused by service loads, while at $\Delta T \geq 40 - 60\ °C$ the calculated values reach levels that may be considered potentially critical for the normal performance of the composite element.

The obtained relationships confirm that, under non-uniform temperature fields across the cross-section, temperature-induced curvature of an element may exert a governing influence on its stress–strain state, especially under conditions of restrained deformability. The deformation patterns presented in Table 2 indicate a transition from weakly expressed curvature at small temperature gradients to significant temperature-induced bending moments in support zones and joints under more intensive heating. This observation is consistent with the results of analytical and numerical studies on temperature-induced bending of steel-reinforced concrete structures.

Comparison of the obtained calculation results with the data reported in previous studies (Zhang et al., 2020; Bai et al., 2023; Zhu et al., 2020) demonstrates both qualitative and quantitative agreement in the growth pattern of temperature-induced bending moments with increasing temperature gradient across the cross-section. Similar levels of temperature-induced bending moments and comparable patterns in the development of thermal curvature of elements have also been reported in the literature, where it is shown that, in statically indeterminate systems, temperature-induced bending moments may reach magnitudes comparable to those caused by service loads and, in some cases, may exceed them (Fan et al., 2022; Zhou et al., 2020; Huang et al., 2023).

Thus, the performed analysis confirms the conclusions of recent studies regarding the necessity of explicitly accounting for temperature gradients across the cross-section in the analysis of steel-reinforced concrete elements. Such consideration is particularly critical for statically indeterminate systems, in which thermal curvature is restrained by supports and fixities. This restraint leads to redistribution of internal forces in supports, beams, and connection zones and may be accompanied by a reduction in the available load-bearing capacity of the structure.

Transverse shear stresses

Transverse shear stresses arising in the steel–concrete connector zone represent one of the most vulnerable aspects of the structural behavior of steel-reinforced concrete structures under temperature actions. They are particularly critical in the presence of a temperature difference across the depth of the cross-section, which leads to relative displacement between the steel and concrete components. Because the steel and concrete parts experience different temperature-induced deformations, significant shear forces develop in the region of the studs, which are transferred and resisted by the shear connectors.

The difference in temperature-induced deformations of steel and concrete is determined according to Equation (8).

The evaluation of relative slip between steel and concrete is determined by the following expression:

$$\delta = \Delta\varepsilon \cdot \frac{p}{2} \tag{14}$$

where, p – spacing of shear studs (anchors);

δ – relative slip, mm.

The shear force in a single stud is determined as:

$$F = K \cdot \delta \tag{15}$$

where, K – stiffness of the steel–concrete connection per single stud.

The utilization factor of the load-bearing capacity of a stud is defined as:

$$\eta = \frac{F}{R} \tag{16}$$

where, R – design load-bearing capacity of a single stud.

The resulting calculation chain (in compact form) can be written as:

$$\eta = \frac{K}{R} \cdot \left((\alpha_s - \alpha_c)\Delta T \cdot \frac{p}{2}\right) \tag{17}$$

For an illustrative assessment of temperature-induced shear in the steel–concrete interface zone, conditionally representative parameters were adopted. These parameters are widely used in studies on the behavior of shear connectors and are consistent with the values applied in a number of experimental and numerical investigations. The spacing of shear studs was taken as $p = 100$ mm, which is typical for steel-reinforced concrete beams and floor systems with full or nearly full composite action. The stiffness of a single shear connector was assumed as $K = 50\ \text{kN/mm}$, corresponding to the elastic stage of stud behavior. The design load-bearing capacity of a single stud was taken as $R = 81{,}7$ kN under normal temperature conditions and $P_{fi}, Rd \approx 7{,}1$ kN under fire exposure, in accordance with data reported in normative documents and scientific literature. The adopted parameters make it possible to reproduce the results presented in Table 3 and are used exclusively to demonstrate the influence of temperature actions on the behavior of the steel–concrete connection zone.

Table 3. Calculation of temperature-induced shear

Scenario	ΔT across steel–concrete interface, $°C$	$\Delta\varepsilon, (\times 10^{-6})$	Slip estimation δ, mm	Shear force in one stud F, kN	Stud resistance R, kN	Utilization factor η
Summer heating from below (non-uniform)	40	80	0.008	0.40	81.7	0.005
Winter cooling from above (non-uniform)	30	60	0.006	0.30	81.7	0.004
Fire exposure	300	600	0.060	3.00	P_{fi},Rd ≈ 7.1	0.42
Note – compiled by the authors						

The calculation results presented in Table 3 indicate that an increase in the temperature difference between the steel and concrete components of a steel-reinforced concrete element leads to higher relative thermal deformations and the development of transverse shear displacements in the steel–concrete interface zone. Under climatic scenarios (summer heating and winter cooling), the calculated shear forces remain significantly below the load-bearing capacity of the stud connectors, which corresponds to low utilization factors.

Under fire exposure, characterized by steep and localized temperature gradients, relative slip and shear forces in the connectors increase by an order of magnitude, and the utilization factor approaches its limiting values. This behavior indicates that the connectors operate in a near-ultimate state and confirms their governing role in ensuring composite action of steel-reinforced concrete structures under severe thermal actions. These findings are consistent with the results of experimental and numerical studies reported in the literature (Zhu et al., 2020; Fan et al., 2022; Bolina et al., 2021).

CONCLUSIONS

1. Within the framework of the conducted review and analytical study, a comprehensive analysis of published scientific works devoted to the influence of temperature actions on the behavior of steel-reinforced concrete structures was performed. Generalization of analytical, experimental, and numerical research results shows that temperature effects are not limited to the role of secondary service actions and, in a number of cases, should be regarded as a significant factor affecting the stress–strain state, redistribution of internal forces, and overall reliability of composite elements. Differences in the thermophysical properties of steel and concrete lead to the development of additional temperature-induced deformations and self-equilibrated stresses, which must be considered in the analysis and design of steel-reinforced concrete structures.

2. The analysis of contemporary studies demonstrates that axial temperature deformations, when free thermal expansion is restrained, may result in the development of additional axial forces in steel-reinforced concrete elements, especially in statically indeterminate systems. Under such conditions, temperature-induced stresses can make a noticeable contribution to the overall stress state of the structure, highlighting the necessity of their inclusion in calculation models alongside conventional service loads.

3. Generalization of studies addressing the influence of temperature gradients across the depth of the cross-section shows that non-uniform heating or cooling of steel-reinforced concrete elements leads to the occurrence of inherent temperature-induced bending effects. These effects may develop even in the absence of external loading and, in certain structural configurations, exert a significant influence on stiffness, stability, and force distribution within the structure. Under intensive climatic and fire actions, temperature-induced bending effects require mandatory consideration in the analysis of statically indeterminate systems.

4. The review of published research indicates that shear connectors in the steel–concrete interface are considered in many studies as one of the most vulnerable components of steel-reinforced concrete structures under temperature actions. Temperature differences across the cross-section may cause relative longitudinal and transverse displacements between the steel and concrete components, leading to increased shear forces in the connecting elements. Under cyclic temperature variations, such actions may, according to the literature, contribute to fatigue-related strength degradation of studs and deterioration of bond in the interface zone.

5. Analysis of published experimental and numerical investigations shows that under fire exposure temperature effects are generally intensified due to a sharp reduction in the strength and deformation properties of steel and degradation of concrete performance. The development of steep temperature gradients, cracking of the concrete component, and reduction in the load-bearing capacity of connectors may, in certain adverse scenarios, lead to partial or complete loss

of composite action and transition of the structure to a non-composite behavior mode, accompanied by a substantial reduction in stiffness and load-bearing capacity.

The conducted review emphasizes the importance of performing the analysis of steel-reinforced concrete structures with comprehensive consideration of temperature actions based on modern scientific research addressing temperature-induced stress–strain behavior, the influence of temperature gradients, and the performance of connecting elements under climatic and fire exposure (Zhang et al., 2020; Bai et al., 2023; Fan et al., 2022; Bolina et al., 2021; Zhou et al., 2020; Huang et al., 2023; Peng & Zhou, 2023; Liu et al., 2022). The design of such structures requires temperature deformations, temperature gradients, the behavior of shear connectors, and potential accidental thermal actions to be treated as essential components of the calculation model. This statement is particularly relevant for performance-based fire assessment of composite systems and for modern structural forms such as castellated beams, prefabricated composite members, and composite walls (Gernay & Elhami Khorasani, 2020; Li et al., 2023; Zhang et al., 2025; Long et al., 2024; Wang et al., 2025).

The scientific novelty of the study lies in the systematization of mechanisms governing the formation of temperature-induced deformations, axial and transverse stresses in steel-reinforced concrete elements, as well as in substantiating the significant role of connecting elements in ensuring reliable composite action under temperature effects. The generalized conclusions obtained may serve as a methodological basis for further theoretical, analytical, and experimental research. Future research perspectives are associated with the development of refined calculation models for temperature-induced internal forces, experimental investigation of the behavior of shear connectors under cyclic thermal and fire exposure, and extension of the analysis to various structural systems and climatic service conditions of steel-reinforced concrete structures.

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