APPLICATION OF HIGH STRENGTH STRANDS AND DUCTILITY ANALYSIS IN CONCRETE

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Abstract

The article discusses the application of high-strength prestressing strands. The 2023 update of Eurocode 2 (EC2) allows the use of steels with higher tensile strength, enabling more efficient designs and better material utilization. Research has explored the properties of these steels and developed design models. These high-strength steels affect bond strength, transfer lengths, and anchorage systems. The article highlights the impact of these steels on structural performance.

Keywords

Prestressed concrete, high strength strand, ductility

1 INTRODUCTION

In recent years, advancements and innovations have become increasingly prevalent across nearly all sectors of the construction industry. These innovations extend beyond construction technologies to materials, which play a crucial role in enhancing efficiency and sustainability in building practices. One of the most significant trends of the past decades has been the growing emphasis on the environmental aspects of construction, with a primary focus on reducing the carbon footprint. This factor is of paramount importance, as the construction sector is among the industries with the greatest environmental impact. Consequently, the development of new materials has shifted towards improving their durability and efficiency, as well as minimizing their negative environmental effects - whether through recycling or innovative production processes with lower energy demands.

Rising demands for efficiency and durability are also evident in the design and execution of structural elements, whether in buildings, bridge structures, or engineering constructions. The primary focus is on increasing structural resilience and reliability. The evolution of construction materials and technologies has demonstrated that conventional structural materials, such as reinforced concrete and traditional reinforcement steel, can no longer fully meet the ever-growing requirements for efficient and economically viable solutions. The increasing demands for higher strength, reduced structural dimensions, and extended service life have necessitated new approaches in structural design, leading to the broader adoption of prestressed concrete [9].

Prestressed concrete has emerged as an innovative solution that enables more efficient load transfer, minimizes deformations, and extends the lifespan of structures. By applying prestressing forces, material consumption can be significantly reduced, resulting in cost savings as well as a lower environmental impact. Due to these advantageous properties, prestressed concrete has become an integral part of modern construction. A key component of this technology is prestressing reinforcement, which allows for the efficient transfer of significantly higher loads, the design of slender structural elements, and the construction of larger-span structures. This principle is based on the introduction of compressive stresses into the concrete prior to the application of external loads, thereby significantly reducing the risk of cracking and enhancing the overall durability and strength of the structure. In addition to its high strength and modulus of elasticity, one of the essential properties of prestressing steel is its ductility. This characteristic allows the reinforcement to absorb considerable deformations without a significant reduction in stress, thereby improving the overall safety and reliability of the structure.

This article focuses on the potential applications of high-strength prestressing steels of higher strength classes. These high-strength steel options are gaining prominence with the introduction of the second generation of Eurocodes.

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2 METHODOLOGY

High tensile strength steel

With the new generation of Eurocodes, several significant changes have been introduced. Due to the wide range of evolving technical and legislative requirements, it has been necessary to adapt the regulatory standards accordingly. The scope of the Eurocodes has been expanded to incorporate new materials and to include chapters dedicated to the design of structures utilizing higher-strength and superior-quality materials. These changes affect the concrete and the reinforcing and prestressing steel. In prestressed concrete applications, now it will be possible to implement prestressing reinforcement with a characteristic tensile strength of Y2060 (Tab. 1).

Tab. 1 Properties in stress-strain diagram (characteristic values) EN 1992-1-1:2023 [1].

STRANDS	Y1770	Y1860	Y1960	Y2060
Proof stress $f_{p0,1k}$ in MPa	1560	1640	1740	1830
Tensile strength f_{pk} in MPa	1770	1860	1960	2060
Stress ratio k=$(f_p/f_{p01})_k$	≥ 1.1			
Characteristic strain at maximum force ε_{uk} in %	≥ 3.5			

Although prestressing reinforcement with a maximum tensile strength of 1860 MPa is currently predominant in the construction industry, as early as 2005, the technical committee proposed a European standard (Tab. 2) for steels with tensile strengths reaching up to 2160 MPa.

Tab. 2 7-wire strands- Dimensions and properties prEN 10138-3:2005 [2].

7-WIRE STRANDS	Y1670	Y1770	Y1860	Y1960	Y2060	Y2160
Tensile strength R_m in MPa	1670	1770	1860	1960	2060	2160
Diameter D in mm	15.2	6.9 – 18.0	6.9 – 15.7	9.0 – 9.3	6.4 – 11.3	6.85
Characteristic value of maximum force/ 0.1% proof force	1.16	1.16	1.16	1.14	1.14	1.14
Characteristic strain at maximum force ε_{uk} in %	≥ 3.5					

In this study, the requirements set forth in ISO 6934-4:2020, which addresses the use of prestressing steel strands in concrete structures, were considered during the comparison of various types of tendons.

Tab. 3 Dimensions and tensile properties of strand ISO 6934-4:2020 [3].

7-WIRE STRANDS	Y1720	Y1770	Y1860	Y2160	Y2230	Y2360
Nominal tensile strength in MPa	1720	1770	1860	2160	2230	2360
Nominal strand diameter in mm	9.3 – 15.2	15.7	9.5 – 15.7	12.7 – 15.2	12.7 – 15.7	12.7 – 15.2
Characteristic value of maximum force/ 0.1% proof force	1.18	1.18	1.18	1.18	1.18	1.18
Characteristic strain at maximum force ε_{uk} in %	≥ 3.5					

This standard provides detailed technical specifications for high-strength steel strands, including their mechanical properties, materials, manufacturing processes, and testing, ensuring their quality and reliability in construction applications (Tab. 3).

The implementation of such high-strength materials opens new possibilities for optimizing prestressed structures and reducing material consumption. The use of prestressing steel is considered a major engineering advancement, as controlled prestressing enhances durability, load-bearing capacity, and overall service life. Prestressing effectively reduces crack formation, thereby minimizing the impact of aggressive environmental factors and slowing down the corrosion process of steel reinforcement. Given that current prestressing strands typically reach a maximum strength of 1860 MPa, the development of higher-strength grades presents new research opportunities, particularly in terms of experimental verification of structural behaviour under extreme loading conditions and long-term operational performance. Investigating the interaction of high-strength prestressing reinforcements with modern concrete mixtures, as well as the development of new anchorage and bonding methods, will be a key aspect of future technical advancements in prestressed concrete structures.

Ductility

Ductility, also referred to as strain capacity, represents the ability of a material or structural component to undergo plastic deformation without failure under high-stress conditions. The production of high-strength prestressing reinforcement involves hot-rolled steel wires with a circular cross-section, containing a maximum carbon content of 0.85%. It is well established that increasing the carbon content enhances the steel's strength but simultaneously reduces its ductility. The mechanical properties of prestressing strands can be further modified through cold working, which increases the steel's strength but concurrently reduces its strain capacity (ε_{uk}) and enhances its brittleness. The ductility of prestressing reinforcement is defined as the ratio of tensile strength to proof stress $(f_p/f_{p0,1})_k$ and the characteristic strain at maximum load ε_{uk}. For high-strength prestressing reinforcement, a guaranteed minimum strain capacity (ε_{uk}) of 3.5% is required (Fig. 1).

According to current standards, as well as the second-generation Eurocodes, prestressing reinforcement is considered to exhibit adequate ductility if the condition $f_{pk}/f_{p0,1k} \geq k$ is met, where the recommended coefficient k is 1.1. Although this coefficient does not directly influence structural design, it plays a crucial role in the specification of prestressing reinforcement.

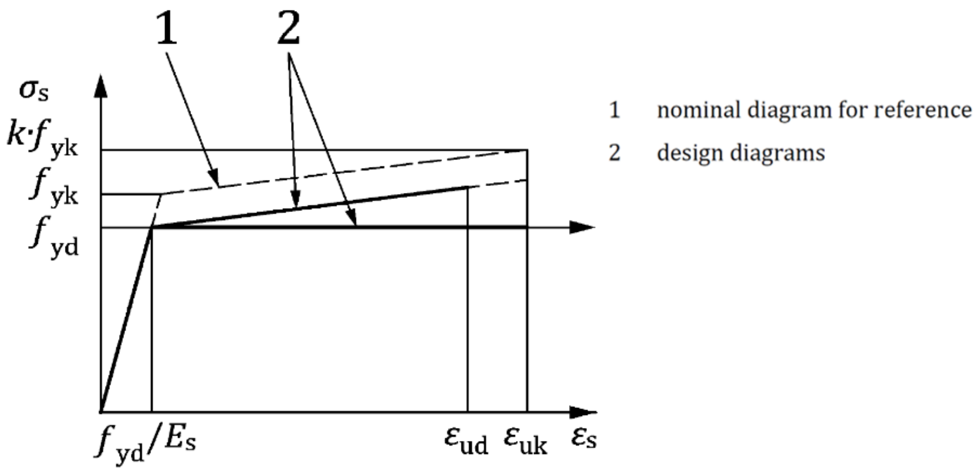

Fig. 1 Stress - strain diagram [1].

Relevant articles about high-strength strands

This paper also includes a review of research studies focused on ultra-high-strength prestressing steel (UHS) conducted worldwide. In recent years, authors of various publications have increasingly concentrated on high-strength steel. The application of materials with new properties raises numerous questions related to structural design. When designing prestressed concrete structures using UHS, it is necessary to address not only conventional design factors but also fundamental parameters such as transfer lengths and anchorage methods. Several publications investigate cross-sections incorporating UHS, including strengths exceeding those specified in the new generation of Eurocode 2 – where the tensile strength of individual prestressing strands reaches

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2400 MPa.
Park Ho and other authors [4], [5] examined the influence of high-strength prestressing strands on the flexural behaviour of post-tensioned beams, based on concrete compressive strength and strand tensile strength. Their findings evaluated structural performance in comparison with current code predictions, regardless of strand tensile strength. In addition to the strand tensile strength, the variable in their study was also the concrete compressive strength [4]. In a second experiment [5], 11 test specimens were analysed, where the variables included the number of strands, cross-sectional shape, strand tensile strength, and reinforcement of the anchorage zone. The study demonstrated that beams reinforced with 2400 MPa strands exhibited a 14.5% higher flexural resistance compared to those with 1860 MPa strands.
In another study, Carin Robert-Wollmann and colleagues [6] investigated differences in transfer lengths and flexural resistance between prestressing strands of 2070 MPa and 1860 MPa strength classes. A total of 10 prestressed beams were manufactured for each strength class. Experimental results confirmed that increasing strand strength affects transfer length, anchorage length, and flexural resistance.
Most studies focused on the evaluation of transfer lengths, including the work of Sun-Jin Han and colleagues [7]. Since most existing transfer length prediction models were derived based on test results from strands with tensile strengths of 1860 MPa or lower, modifications to these models are now necessary to account for the effect of increased prestressing strand strength. In their study, six prestressed concrete specimens reinforced with 2400 MPa prestressing strands were produced and tested to analyse their transfer lengths.
Further investigations into transfer lengths were carried out by Yang Jun-Mo and colleagues [8]. Their study experimentally evaluated the transfer length of seven-wire high-strength strands with a tensile strength of 2400 MPa and a diameter of 15.2 mm in prestressed concrete beams using concrete with a compressive strength greater than 58 MPa at the time of prestressing. A total of 32 specimens were produced, varying in concrete compressive strength, cover thickness, and the number of strands, with corresponding transfer lengths measured. The experimental results demonstrated that transfer length decreased with increasing concrete compressive strength and cover thickness.

3 PARAMETRIC ANALYSIS

To quantify the influence of selected mechanical properties of high-strength prestressing strands on the behaviour of concrete elements, a numerical parametric analysis was conducted. The variable parameters within this analysis included the ultimate tensile strength (f_{pk}) of the prestressing strands and the ratio of tensile strength to the 0.1% proof stress ($(f_p/f_{p0,1})_k$), characterized by the coefficient k, which reflects the material's ductility.
The numerical model was developed using the Atena 3D software, which enables advanced nonlinear analysis of reinforced and prestressed concrete structures (Fig.3). The analysed beam was modelled as a full 3D solid, with geometry, support conditions, loading, and reinforcement layout consistent with the experimental setup (Fig. 2), which served as an indicator of the influence of coefficient k on the global structural behaviour and the effect of tensile strength on the load-bearing capacity. The total length of the analysed specimen was 7.0 m, with an effective span of 4.9 m. Fig.2 illustrates the experimental setup of the real-scale test, which served as the basis for the calibration of the numerical model.
The concrete was modelled using the improved B3 model, corresponding to concrete class C50/60 with characteristic compressive strength f_{ck}=50MPa and a modulus of elasticity E_c=30,32 GPa. To account for the time-dependent effects such as creep and shrinkage, the B3 Improved material model was employed in the numerical analysis. This model is based on the well-established B3 theory and provides improved accuracy for high-strength concrete under long-term loading. The supports and loading were applied as boundary conditions to simulate the experimental setup, using rigid plates to avoid stress concentration.
In the parametric study, the stress – strain behaviour of prestressing steel was defined using an idealized bilinear diagram with a linear elastic branch up to 0.1% of proof stress $f_{p0.1k}$, followed by a hardening branch up to the ultimate tensile strength (f_{pk}). The slope of the hardening branch was controlled by the ductility coefficient k, defined as the ratio $(f_p/f_{p0,1})_k$, and varied across the different specimens. Characteristic strength values were used in all models to ensure consistency with the design assumptions. The limiting strain (ε_{uk}) was set to a constant value of 3.5% for all specimens, as recommended in design standards. Initial prestressing losses were accounted for by reducing the initial stress in the strands to approximately 80% of f_{pk}, simulating effective prestress at the time of loading. The same initial stress levels were applied across the different configurations to isolate the influence of the mechanical parameters.
The beam was reinforced with longitudinal reinforcement of 5 mm in diameter, placed at both the top and bottom surfaces of the cross-section, in order to minimize the impact of reinforcing steel. Additional bars of the same diameter were incorporated to satisfy structural detailing requirements. Transverse shear reinforcement consisted

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of double-legged stirrups with diameters of 6 mm and 8 mm respectively, which were densely spaced in the central region of the beam.
In this analysis, a real-scale beam originally designed for the investigation of shear resistance was used as the basis for model calibration. Despite the current study focusing on flexural resistance, the transverse reinforcement layout remained unchanged.
Additionally, the beam was reinforced with six prestressing strands of 15.7 mm in diameter. Among these, four strands were positioned at the bottom surface, while two strands were placed at the top surface of the beam. The prestressing reinforcement was pre-tensioned to the following average initial stress values at the time of prestressing:

- $\sigma_{p,max}$=1488 MPa for prestressing strands with a tensile strength 1860 MPa,
- $\sigma_{p,max}$=1968 MPa for prestressing strands with a tensile strength 2460 MPa.

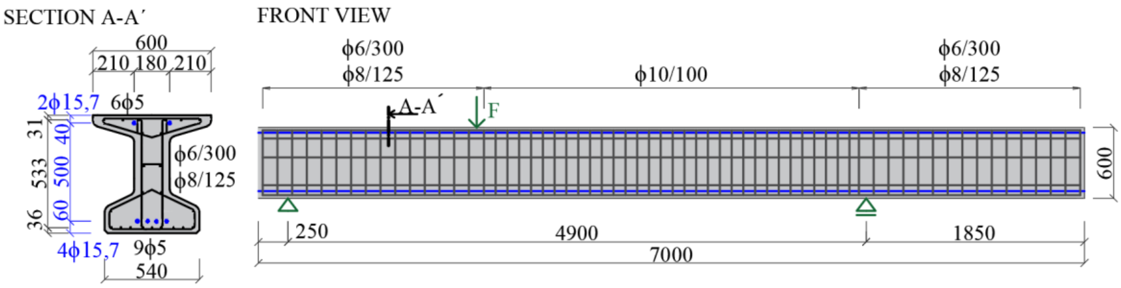

Fig. 2 Analysed beam.

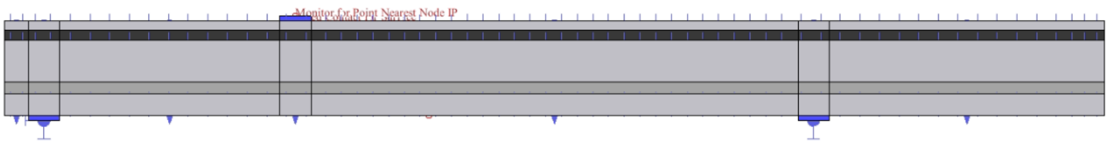

Fig. 3 Model created in Atena software.

A total of four experimental test models were analysed, with the primary variable parameters in the numerical study being the nominal tensile strength of the prestressing strands and the ductility coefficient *k*, which characterizes the ratio of tensile strength to the 0.1% proof stress limit (Tab. 4). The objective of this analysis was to assess the influence of these parameters on the global mechanical behaviour of the examined structural elements, particularly in terms of their deformation capacity, load-bearing limit, and crack propagation within the concrete structure.

Tab.4 Variable parameters applied in the numerical analyses.

	Tensile strength in MPa	**Ductility coefficient *k***
Specimen 1	1860	1.1
Specimen 2	1860	1.05
Specimen 3	2460	1.1
Specimen 4	2460	1.05

4 RESULTS

Based on the data presented in Fig. 4, the resistance of the cross-section when using tendons from higher strength classes was evaluated. The results clearly demonstrate that the use of tendons with a tensile strength of 2460 MPa led to specimen failure under a load that exceeded the failure load of the specimens reinforced with tendons of 1860 MPa by more than 23%. This outcome confirms the initial assumption that tendons with higher tensile strength significantly enhance the material's resistance to load-bearing forces, thereby increasing the overall structural performance.

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Furthermore, the magnitude of the observed deformation is significantly influenced by the ductility factor *k*. In the elastic region of the load-deflection diagram, the behaviour of specimens reinforced with tendons of the same strength class was shown to be identical. However, a substantial difference in deformation behaviour was observed in the plastic region, which can be attributed to the increased ductility factor in the higher-strength class tendons. Specifically, tendons with a higher value of *k* allowed for larger deformations without material failure, highlighting the importance of ductility in the material's ability to withstand plastic deformation under high loads.

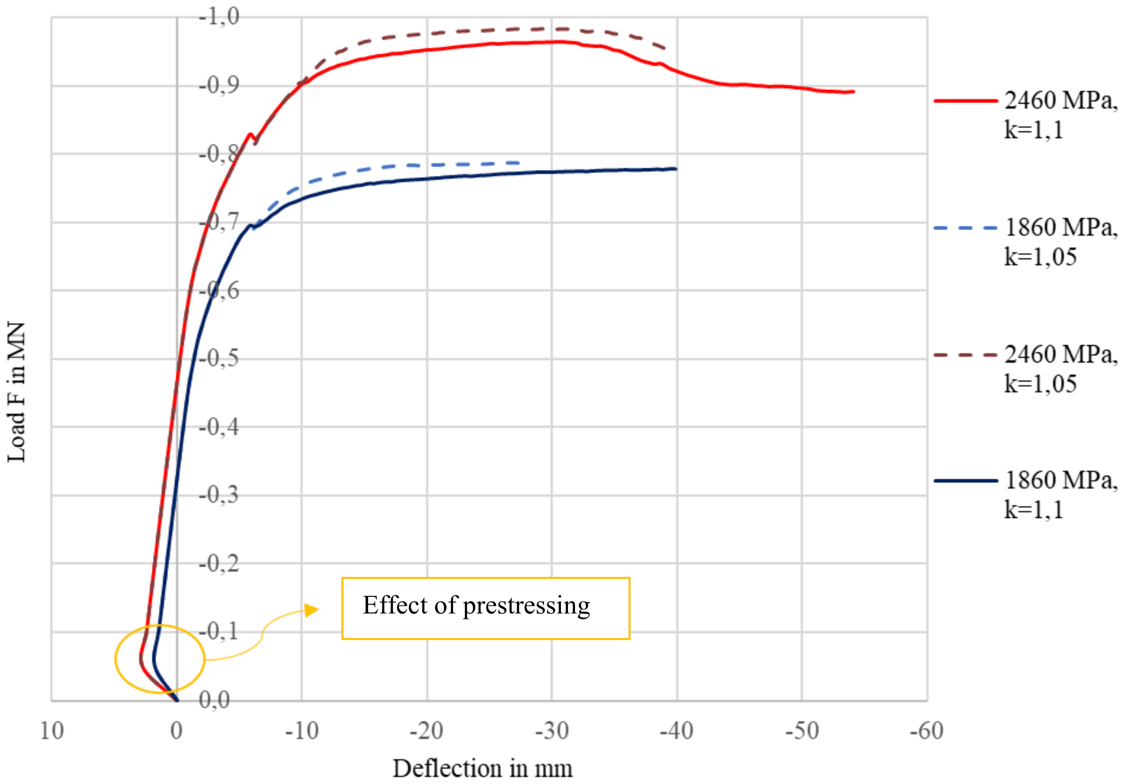

Fig. 4 Load-Deflection Relationship.

Tab.5 Variable parameters applied in the numerical analyses.

	Tensile strength in MPa	**Ductility coefficient *k***	**Maximum applied load/failure load in MN**	**Deflection in mm**
Specimen 1	1860	1.1	0.778/0.778	39.9
Specimen 2	1860	1.05	0.787/0.787	28.1
Specimen 3	2460	1.1	0.964/0.891	54.1
Specimen 4	2460	1.05	0.984/0.953	39.2

Based on the stress distribution outputs from the numerical simulation, it was observed that, immediately prior to failure, the tensile stress in the prestressing reinforcement exceeded the defined tensile strength limit. This stress level corresponds to the ultimate tensile capacity of the strands, indicating that the rupture of the reinforcement was imminent. Following the peak load, a sudden drop in the stress values was detected, confirming that failure occurred due to the tensile rupture of the prestressing strands. Although cracks were observed in the concrete during the analysis, and localized crushing occurred beneath the loading plate, these phenomena did not govern the overall failure mechanism. The decisive factor remained the tensile failure of the reinforcement.
The distribution of tensile stress in the prestressing reinforcement just before failure for all analysed specimens is presented in the following figures (Fig. 5, Fig. 6, Fig. 7 and Fig. 8).

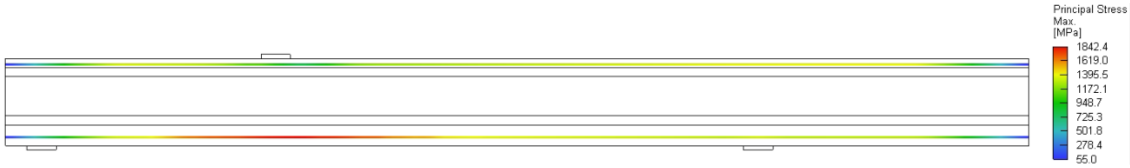

Fig. 5 Specimen 1.

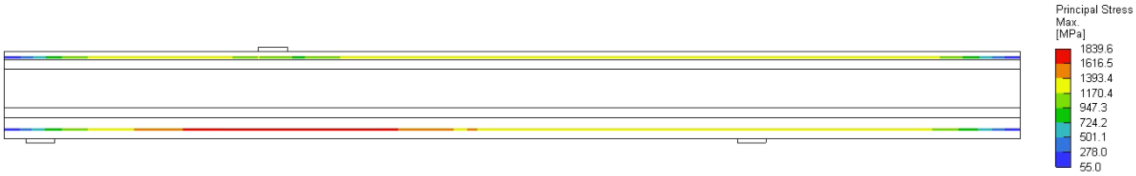

Fig. 6 Specimen 2.

Fig. 7 Specimen 3.

Fig. 8 Specimen 4.

4 DISCUSSION

Even though specimens with a lower *k*-value exhibited smaller deformations and failed earlier, the maximum applied load values were consistently higher in the beams reinforced with high-strength steel tendons. This difference is particularly significant in applications where high load-bearing capacity is required without excessive deformation prior to failure. The results suggest that high-strength steel, even when exhibiting lower ductility, can provide substantial advantages in specific technical applications where the primary requirement is high material strength rather than extensive plastic deformation.

This insight is crucial for designing structural elements that must withstand extreme loads, as the higher tensile strength of the tendons directly influences their performance under these conditions. However, the trade-off in terms of ductility must also be considered in these applications to ensure that the material performs as expected under both elastic and plastic deformation conditions.

Further detailed results can be found in Tab. 5, which presents a comprehensive overview of the specific load values and corresponding deformations based on tendon type and strength class. These data offer additional insights into the relationship between the material properties of the tendons and their performance in structural applications, aiding in the optimization of tendon selection for various engineering projects.

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5 CONCLUSION

Based on the conducted literature review, it can be concluded that high-strength prestressing steels offer significant potential in the field of construction by enhancing the efficiency of structural systems. In particular, the application of prestressing strands with higher strength classes contributes to a notable increase in the flexural resistance of load-bearing elements. However, modifications to anchorage systems are required to accommodate these materials in practical applications. While their implementation enables improved structural resistance, it is also essential to consider technological challenges and the necessary engineering solutions associated with their use. The findings of the parametric study confirmed the anticipated mechanical properties of high-strength steels concerning cross-sectional resistance. However, a key parameter influencing the structural response, particularly in the plastic regions of the load-deflection relationship, is the ductility coefficient k. When utilizing the recommended value of k=1.1, the achieved deformation was over 27% greater compared to a specimen with k=1.05. The influence of variations in the ductility coefficient was particularly pronounced in prestressing strands of higher strength classes. While slightly higher failure loads were observed, the use of a lower ductility coefficient k=1.05 had a detrimental effect on the deformation capacity at failure, leading to reduced ductility.

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