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NONLINEAR PUSHOVER ANALYSIS OF PRESTRESSED CONCRETE BEAM

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Abstract. This study investigated nonlinear pushover analysis of prestressed concrete beam using the DIANA FEA (Finite Element Analysis) software that embraces 1D, 2D, and 3D modeling methodologies. In engineering structures, the use of prestressed concrete is indispensable because it remarkably enhances the load-carrying capacity by imposing precompression that reduces tensile stresses, which can lead to cracking and deflection. Study investigates the behavior of prestressed concrete beams, focusing on load-displacement relationship and crack propagation. A case study examined the accuracy of the numerical simulations with respect to the empirical results by comparing different modeling methodologies using experimental studies from a case study performed earlier. The research also points out that tendon configuration, prestress magnitude, and concrete durability are some of the main factors that determine the beam functionality. The results show that there is good agreement between the experimental data and numerical predictions for all three modeling approaches (1D, 2D, and 3D) in representing the load-displacement characteristics and the mechanisms of crack initiation, which represents the reliability of numerical models in predicting the structural response. This research will contribute to better decision making regarding modeling techniques and, consequently, help provide better structural integrity and safety in engineering projects.

Keywords: Prestressed Concrete, nonlinear analysis, finite element analysis (fea), modeling techniques, DIANA FEA, concrete, post-tensioned concrete, pushover analysis

GƏRGİNLƏŞDİRİLMİŞ BETON TİRİN QEYRİ-XƏTTİ STATİK ANALİZİ

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Xülasə. Bu tədqiqat gərginləşdirilmiş beton tirlərin DIANA FEA (Sonlu Elementlər Analizi) proqramından istifadə edərək, mühəndislikdə geniş tətbiq olunan qeyri-xətti statik analizini araşdırmışdır. Tədqiqatda, gərginləşdirilmiş beton tirlərinin davranışı, xüsusilə yük və deformasiya arasındakı əlaqə, eləcə də çatların necə yayıldığı öyrənilmişdir. Gərginləşdirilmiş beton, əvvəlcədən tətbiq edilən sıxılma nəticəsində dartılma gərginliklərini azaldır və bununla da çatlama və əyilmə ehtimalını minimuma endirərək strukturun daşıma qabiliyyətini artırır. Tədqiqat çərçivəsində, 1D, 2D və 3D modelləşdirmə üsulları müqayisə edilmiş və onların dəqiqliyi eksperimental məlumatlarla uyğunlaşdırılaraq qiymətləndirilmişdir. Tədqiqat göstərmişdir ki, tendonların quruluşu, əvvəlcədən tətbiq edilən gərginlik dərəcəsi və betonun dayanıqlılığı tirlərin funksional effektivliyinə təsir edən əsas amillərdəndir. Nəticələrə görə, hər üç modelləşdirmə yanaşması (1D, 2D və 3D) yük və deformasiya arasındakı əlaqəni və çatların yaranma prosesini düzgün şəkildə təsvir edir. Bu, rəqəmsal

modellərin struktur davranışını dəqiq proqnozlaşdırmaq üçün etibarlı olduğunu göstərir. Bu araşdırma, mühəndislərin modelləşdirmə üsullarını seçərkən daha düzgün qərarlar qəbul etməsinə kömək edəcək və nəticədə struktur təhlükəsizliyinin və davamlılığının təmin edilməsinə töhfə verəcəkdir.

Açar sözlər: Gərginləşdirilmiş beton, qeyri-xətti təhlil, sonlu elementlər metodu (fea), modelləşdirmə texnikaları, DIANA FEA (Sonlu Elementlər Analizi), beton, sonradan gərginləşdirilmiş beton, qeyri-xətti statik təhlil.

Introduction. Prestressed concrete is a major element in several engineering structures including bridges, skyscrapers, and marine applications. The principal advantage of this technique lies in the process of prestressing, which enhances the capacity of the concrete to support the tensile stresses that would otherwise have caused serious cracking and deflection. Prestressed concrete members can obtain superior performance and durability owing to the application of a predetermined compressive force for a certain purpose before service loads are applied. The method developed at the beginning of the 20th century by French Engineer Eugène Freyssinet became one of the signature elements of modern civil engineering, evolving with improvements in materials, design codes, and numerical methods. [1,2].

FEA is considered to be one of the most universal methodologies for prestressed concrete beams, both in academic circles and in industrial practice. This includes the availability of sophisticated FEA tools, such as Diana FEA, capable of detailing the complex interactions that occur between prestressing tendons and concrete material. According to Zienkiewicz et al. (2005), FEA is a computational method for solving problems that can be formulated with the help of differential equations; hence, nonlinear behaviors such as cracking, plasticity, and creep are easily simulated using this analysis method [3]. Breña and MacGregor (2003) observed that through numerical modeling, it is possible to obtain a proper appreciation of the mechanism through which stress transfer develops between tendons and concrete, especially around anchorage regions where large concentrations of stresses occur [4]. Yapar et al. (2015) employed FE to model concrete beams with several prestress levels and tendon configurations and concluded that the program could precisely predict both crack formation and maximum failure load [5].

Methods. This notwithstanding the fact that numerical analyses have gained widespread application in studies related to prestressed concrete beams. There are still distinctive gaps in the literature because so many studies relate to static loading conditions, while few studies on extreme or dynamic conditions exist, such as seismic or blast loads. Furthermore, fully comparative studies need to be conducted on numerical models with different dimensional approaches using 1D line elements, 2D shell models, and 3D solid models. All of these bear majorly on the accuracy with regard to the way stress is distributed, how cracks propagate, and how the beam behaves as a whole. The present study attempts to fill some of the existing gaps by carrying out an extensive numerical analysis of a prestressed concrete beam using Diana FEA. Various modelling methodologies (1D, 2D, and 3D) are considered in the investigation to test their effectiveness in predicting the behavior of the beam under different loading scenarios. These results will be compared with the test results already obtained and sensitivity studies conducted to ascertain the effect of key factors, such as tendon geometry, magnitude of prestress, and concrete strength, on beam performance. The comparison approach in this regard will provide further insight into both the strengths and limitations of each analysis method.

Within the context of case study analysis and based on extended empirical research data, an important experiment was conducted by Tao and Do in 1985 [6], discussed at length in the PhD thesis written by Bashirzade [7]. The results of their research provided valuable information about the behavior of prestressed concrete beams under different loading types. This thesis carefully reanalyzed the experimental results of Tao and Du, underlining aspects such as tendon arrangement, concrete strength, and the load-deflection relationship. Experimental data in those studies were adopted in the present research to verify the accuracy of each numerical model in Diana FEA-1D, 2D, and 3D, with the aim that numerical simulations are able to capture real behavior, thereby enhancing the robustness of the parametric analysis. [8,9].

Case study. Tao et Du (1985) investigated the flexural strength of unbonded and bonded tendons in partly prestressed concrete beams as a function of prestressed reinforcement strengthening. From both experimental and analytical perspectives, twenty-two unbonded and four bonded partly prestressed concrete beams were assessed [6]. The test results indicated that the analytical and experimental data were similar. The ultimate strain of the unbonded tendons was estimated using the following empirical equation. This study uses the moment-acrylic Nonlinear pushover analysis method to develop analytical programs to improve the stress increase in tendons in the final boundary state, because the plane section assumption cannot be applied to the strain of unbonded tendons in prestressed concrete beams under loading. The test parameters included the loading type, non-prestressed reinforcement ratio, prestressed reinforcement ratio, and span-height ratio. The results of these tests, referred to as “A9” beam in the literature, were examined for DIANA modeling in this study [10].

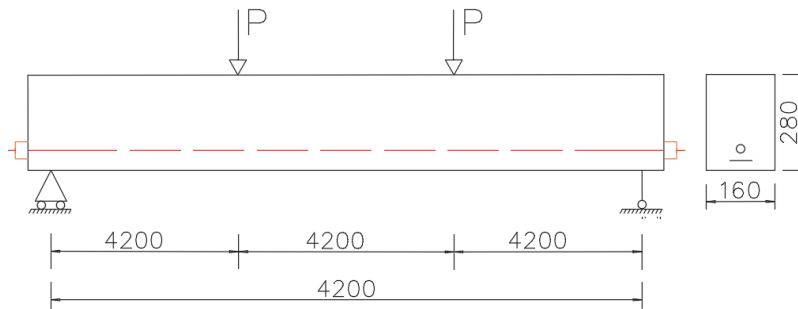


Fig. 1. Experimental loading model (Tao & Du, 1985)

Different loading strategies and failure mechanisms have been investigated in this study. For the concrete and embedded reinforcement, finite element models were developed using 1D line elements, 2D elements, and solid or plane stress elements. Total Strain Crack models were used to simulate concrete, and nonlinear studies were conducted until failure. The concrete model was modeled with exponential softening in tension and Hognestad curve behavior during compression [11] (Fig. 2 a,b). All reinforcements and prestressed tendons were modeled as embedded with adherence-slip reinforcement [12,13]. The material model was based on Von Mises plasticity with linear plastic hardening based on experimental properties. The main purpose of these analyses is to verify the experimental tests as much as possible, using detailed finite element models and advanced nonlinear procedures.

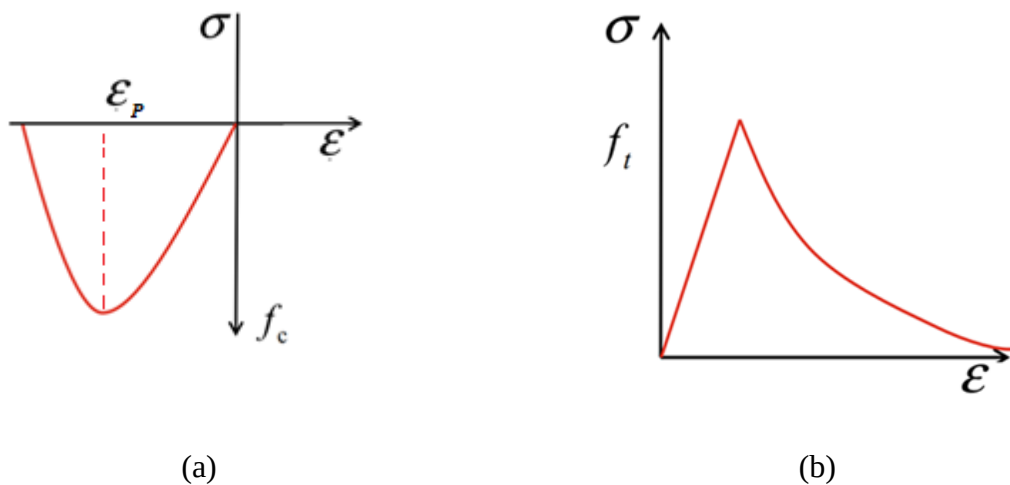


Fig. 2. Concrete compression (a) and tension (b) curve

The material parameters were considered to properly represent the behavior of the beams under the loading conditions. The concrete material was modeled as a nonlinear isotropic material with a maximum compressive strength of 33.1 MPa. Stress-strain curves were used to account for nonlinear behavior. The concrete model accounted for the consequences of cracking and crushing as the load was increased. The unbonded tendon prestress after the loss was set to 920 MPa. These tendons are crucial for strengthening the beams, decreasing the impact of tensile loads, and regulating fracture development. The numerical models also contained non-prestressed reinforcements. The area of the nonprestressed reinforcement was 804 mm², which contributed to the total tensile strength of the beams. The yielding strength of the prestressed reinforcement was 1108 MPa and that of the non-prestressed reinforcement was 395 MPa. To evaluate the load-displacement behavior, an FE model was built using 1D line, 2D shell, and 3D solid elements corresponding to the concrete and bar elements to represent the post-tensioned tendon and non-pre-stressed reinforcement. The modeled tendon was unbonded to the surrounding concrete.

Analysis strategy. During the analysis phase, the prestressed concrete beam was subjected to incremental point loads until it failed. Three modeling techniques (1D, 2D, and 3D elements) were used to investigate the characteristics of the load-displacement behavior. The numerical models were subjected to 100 increments of point loads with a factor of 2.5 imposed at each step to evaluate the load-displacement behavior. The applied loads were increased progressively until the beams failed. The initial linear-elastic range of the beam response was established by a linear connection between the applied load and deflection, followed by nonlinear behavior owing to the fracture initiation and propagation. The arc length control (updated normal plane approach) was set to follow the response path using automated load step scaling. The Newton-Raphson method, with a maximum of 25 iterations and a line search approach, was used to ensure stability and efficiency. If convergence was not obtained within the maximum number of iterations, the analysis proceeded, ensuring a rigorous evaluation of the load-displacement response of the beams until failure. The accuracy and dependability of the validated numerical models in forecasting the structural behavior of reinforced concrete beams under various loading scenarios were validated by comparing them with experimental data. The capacity of the models to effectively reflect the complicated fracture initiation and propagation mechanisms within the beams was proven by the continuous agreement between experimental and numerical data.

Results and Discussion. The analysis of prestressed concrete beam using various modeling approaches (1D, 2D, and 3D solid elements) provided significant details on their load-displacement behavior as well as crack initiation and propagation processes. When the load-displacement curve from practical testing was compared to the numerical simulations, a high degree of agreement was observed, verifying the reliability and precision of the numerical models in presenting the complex behavior of the prestressed concrete beam (Fig. 3). The numerical approach accurately predicted the structural reaction of a beam under loading. In the load-displacement graphs, both experimental and numerical data showed comparable behaviors. A linear relationship between the applied load and deflection was observed in the early linear-elastic range, as predicted for the entire beam. The Load-displacement curves showed this nonlinearity, suggesting the start of deterioration within the beams.

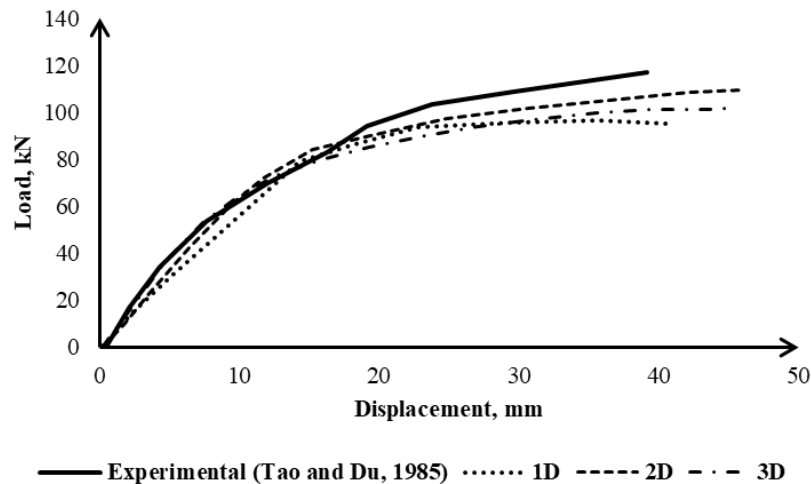


Fig. 3. Load-displacement curves of prestressed concrete beam

The numerical models accurately predicted the critical load levels at which the cracks occurred and propagated throughout the beam (Fig. 4.). The crack propagation locations and patterns of the experimental and numerical simulations were similar, confirming the capacity of the numerical model to accurately represent cracking behavior.

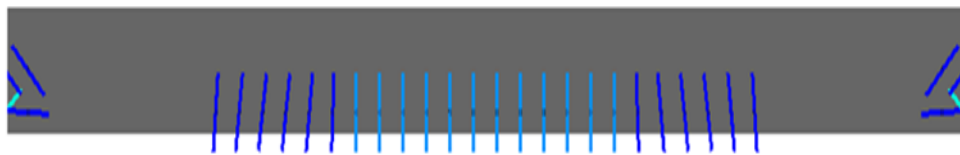


Fig.4. Crack distribution at failure in numerical model of prestressed concrete beam

The results of this study contribute significantly to our understanding of prestressed concrete beam analyses. The verified numerical models may be used as reliable resources in subsequent designs and analyses, enabling more precise predictions of the load-displacement response of prestressed concrete beams under loading conditions. In conclusion, the numerical analysis based on Tao and Du's (1985) study employing 1D, 2D, and 3D solid element models successfully captured the load-displacement behavior as well as crack initiation and propagation processes in prestressed concrete beams. The strong agreement between the experimental and numerical results confirmed the reliability of the numerical approach and provided critical insights for the design and analysis of prestressed concrete beams in real engineering applications.

Conclusion. In this study, an elaborate Nonlinear pushover analysis of a prestressed concrete beam was performed. To perform this test, the DIANA FEA software was utilized using 1D, 2D, and 3D elements in the modeling. The research followed up on the failure that occurred in the beam, while studying in detail the correlation between crack formation and load-displacement. These results showed that the 1D, 2D, and 3D models matched well with the experimental data; the closest approximations were from the 3D model. Additionally, during the failure phase, all three models yielded similar results. From this observation, it follows that any of the three models can provide sufficiently consistent results in a wide analysis of prestressed concrete beams. Therefore, these analyses can be used to enable better and more informed decision making regarding the choice of modeling techniques in engineering design.

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