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Evaluation of Pre-tensioned Prestressed Concrete Beam Behavior by Finite Element Analysis Using ATENA 3D

Zaher Alkurdi [1]
[1] Budapest University of Technology and Economics
Műegyetem rkp. 3, 1111, Budapest, Hungary
zaherkurdi@edu.bme.hu

Abstract - This research involves a numerical study of the nonlinear behavior of pre-tensioned prestressed concrete beams with multiple layers of strand and shear reinforcements under flexural loading. Validation of the model was performed based on the results of the standardized four-point static bending test reported in previous experimental research. The ATENA 3D software could simulate the experimental tests and provide meaningful results. Moreover, it is possible to express the behavior of four-point bending test by using ATENA 3D without attribution on an experimental but based on a validated one model. This saves the effort and cost needed to prepare and conduct the laboratory test.

***Keywords*:** Prestressed concrete, numerical analysis, four-point static bending test

1. Introduction

Reinforced concrete is a structural material that is extensively utilized in civil engineering. A reinforced-concrete building system is the most lasting and low-maintenance solution. To achieve equilibrium and control of deformation following cracking, reinforcement is inserted in the concrete [1]. Concrete production contributes significantly to the climate catastrophe by emitting massive volumes of carbon dioxide into the atmosphere. Carbon dioxide and methane are the two greenhouse gases mainly responsible for global warming. Furthermore, concrete can harm the earth's most fertile layer, the topsoil [2–3].

Prestressing is an important stage in reinforcement since it reduces the quantity of concrete required, lowering material usage and transportation costs while increasing durability and service life [4]. A prestressing system is used to take advantage of its compressive strength. Prestressing compresses the concrete structure in places where load causes tensile stress. Before cracking in the concrete develops, the tension created by applied loads must first relieve the compression caused by the prestressing, which is performed with tendons [5]. When reinforced with steel, concrete can bear significant tensile loads while also exhibiting excellent ductility, allowing structural elements to fail in a ductile manner with extensive plastic deformation when overloaded. This type of failure is known as a flexural failure. With the capacity to provide sufficient warning before failure, this type of failure is commonly used in the design of a structural element. When specific design standards are followed, this behavioral response can be correctly predicted. The four-point static bending test is used to investigate the properties and behavior of materials with structural applications, thus establishing design specifications.

Numerical modeling has made considerable progress in this area. Furthermore, numerical modeling is being implemented in design because experiments can be challenging, costly, and time-consuming [6]. In addition, model predictions closely align with experimental testing. As for modeling a pre-tensioned prestressed concrete beam, the most common user-friendly software packages for the nonlinear analysis of reinforced-concrete structures are ATENA 3D, ANSYS, and ABAQUS. In particular, ATENA 3D, based on advanced constitutive models, can effectively support and extend experimental investigations for innovative solutions in the field of prestressed concrete members. The crack-band approach employed for tensile and compressive softening avoids the finite element (FE) mesh sensitivity of the solution.

Tavares et al. [7] studied bond behavior for different bar diameters with simulated pull-out tests using ATENA software. Their numerical results were in the range of experimental results. Furthermore, Yapar et al. [8] presented a nonlinear FE model for pre-tensioned prestressed concrete beams using ABAQUS software. Up to the collapse load, the modeling and simulation results for the test problem were quite close to the test results. The simulation results provided a good explanation of how such beams behave.

Similarly, Hoang et al. [9] developed a FE model in ATENA 3D to examine the compressive behavior of circular steel tube–confined concrete stub columns using various concrete compressive strengths, including normal, high, and ultra-high strengths. The FE model predicted curves of ultimate and axial loads versus vertical strain that aligned well with those of previous test results. Additionally, Abed et al. [10] simulated pull-out tests using ATENA 3D software. The numerical results were comparable to those obtained experimentally, which expressed real behavior.

As discussed, several experiments have been simulated using various software where the numerical results align with those of experimental tests. Although several reinforced-concrete member models have been simulated, few numerical models are available in the literature on the flexural behavior of the pre-tensioned prestressed members. Therefore, more research is needed to numerically model the flexural behavior of a pre-tensioned prestressed concrete beam accurately and understand the important parameters involved.

2. Methodology

Based on an experimental investigation from the literature review, this study consists of numerical modeling efforts targeted at understanding and validating the structural behavior of a pre-tensioned prestressed concrete member. A four-point static bending test is used to perform the flexural test on the pre-tensioned prestressed concrete beam. Cowen and VanHorn [11] carried out an experimental study on a simply supported T-beam. As shown in Fig. 1, the specimen was a rectangular prestressed concrete beam with a cast-in-place slab. In this study, the ATENA 3D software was used to simulate the actual behavior of concrete structures, such as reinforcement yielding, concrete cracking, and crushing [12]. Furthermore, ATENA 3D was specially designed for concrete, making it more user-friendly with appropriate default values.

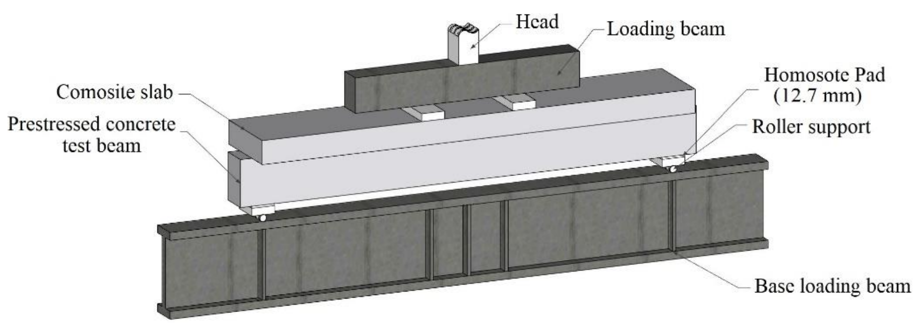

Fig. 1: Four-point static bending test.

The concrete mix was produced with Type III (high-early strength) Portland cement, sand, and crushed limestone coarse aggregate (3/4 inch, or 19 mm, maximum). The proportions of the mix by weight (cement-to-sand-to-coarse aggregate) were 1.00:2.64:2.98. The cylindric concrete compressive strengths at the time of the test were 41.16 MPa and 46.56 MPa for the rectangular beam and slab, respectively. In addition, Young's modulus of the concrete was 28 GPa.

In this study, stress-relieved type seven-wire 270 K strands with a diameter of 12.8 mm were used as longitudinal reinforcements. The elastic modulus of the strand is 200.595 GPa, as determined by Cowen and VanHorn [11]. These strands were located in three layers within the cross-section, as shown in Fig. 2. The rebars for the shear reinforcements were fabricated from No. 3 deformed bars with a nominal yield stress of 345 MPa and a diameter of 10 mm.

2.1. Four-point static bending test

In this section, the laboratory experiment of the four-point static bending test related to Cowen and VanHorn [11] is presented and validated using the nonlinear FE software ATENA 3D. The test was carried out to determine to expected ultimate load and the associate failure characteristics.

The pre-tensioned prestressed concrete beam was tested in the Fritz Engineering Laboratory's 300 kips (1334.5 kN) hydraulic testing machine [11]. As illustrated in Fig. 1, the loading beam and associated apparatus were arranged to provide provide symmetric two-point loading for the specimen. The pre-tensioned prestressed concrete beam used in this study had had a span of 2743.2 mm. Figure 2 shows the geometry, beam cross-section, and position of the loading spins. The test specimen was initially loaded in increments of 44.5 kN, which approximated to around 8% of the computed ultimate load. load. When cracking of the concrete became visible, the loading increment was reduced to 22.25 kN until failure occurred. occurred. The strands were initially tensioned to a stress level of 70% of the specified ultimate stress [11]. Table 1 presents presents the measured losses in the strand.

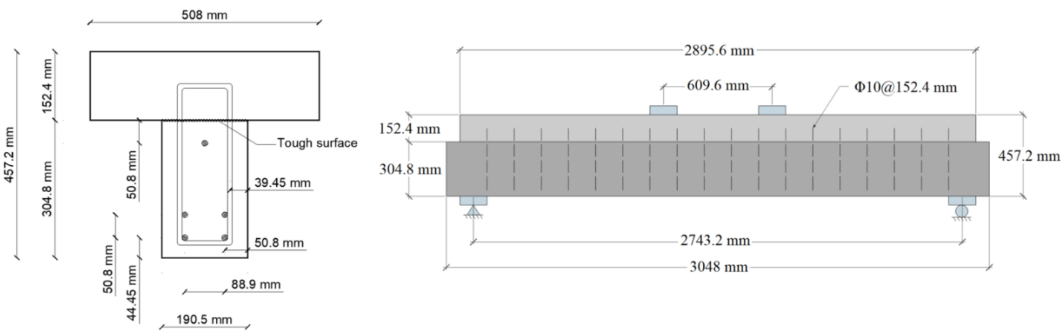

Fig. 2: Schematic and cross-section of the pre-tensioned prestressed concrete beam.

Table 1: Losses in prestressing strand [11].

Initial stress (kN)	Elastic loss at release (kN)	Stress after release (kN)	Percent loss after release %	Shrinkage (kN)	Creep ,steel and concrete (kN)	Total loss (kN)	Total loss present %	Effective stress (kN)
128.55	15.03	113.52	11.70	19.88		34.91	27.20	93.64

After establishing the model geometry and the flexural bond test procedures used in the experiment, an inverse analysis was executed by ATENA 3D. To simplify the calculations, half of the pre-tensioned prestressed concrete beam was modeled, owing to symmetricity. Steel plates 3 cm thick were placed at the bottom of the beam for support and at the top of the beam for loading. To avoid early cracking, the displacement stresses were applied at the upper steel plate rather than directly on the beam, as indicated by the software manual [13]. An elastic tetrahedral element with an elastic modulus of 2.1×10^5 MPa was used to model the steel plates. For the boundary conditions, since analyzing only half of the beam, the axis of symmetry along the right side of the beam was enforced. Therefore, the horizontal y-displacements along this side should be equal to zero. The transition of the left support was fixed in the vertical and lateral directions, as illustrated in Fig. 3. The FE mesh type for the model was brick with a size of 0.05 m. The loading history for the analysis was defined, consisting of load steps, and each load step included a combination of load cases. In the software, the Newton-Raphson solution method was chosen. The simulation's aim was to increase the load to failure. Forces, displacements, strains, and stresses in the model are typically monitored during nonlinear analysis. The monitored data can provide information about the model's status and produce the load-deflection curve. Therefore, two monitoring points were selected in the numerical model for this purpose (see Fig. 3). The first point was for the monitoring of the force applied at the top steel plate. The second point was located at the middle of the beam near its bottom surface, where the largest vertical displacements could be expected. Thus, the required load-deflection curve could be obtained. In addition, other monitor points were defined to record the stresses, strains, and crack widths of the member.

When defining the materials, the compressive strength of concrete was entered into the program for the slab (flange) and the beam (web). The strand properties were defined according to the experiments, as shown in Fig. 4. In addition, prestressing forces were applied to the strands in the software in the form of an effective stress of 93.64 MPa.

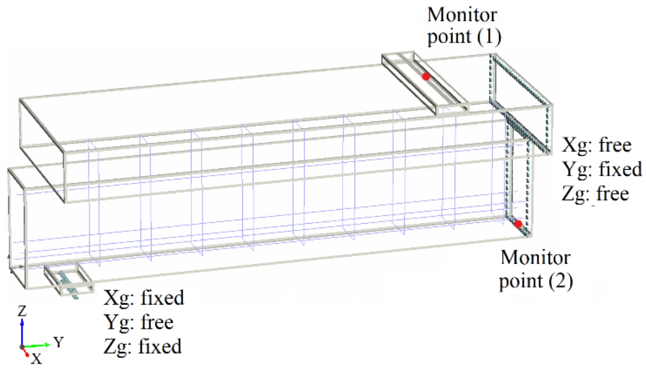

Fig. 3: Program displays of the four-point bending model and the location of the monitor points.

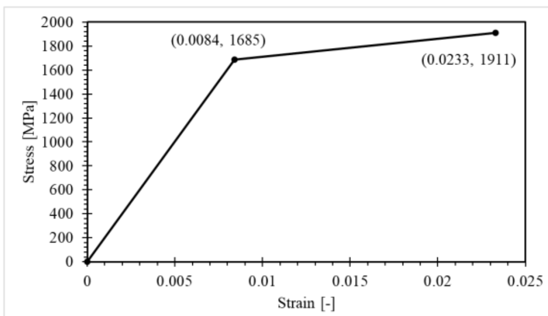

Fig. 4: Stress-strain curve for the seven-wire strand used in ATENA 3D.

2.2. Nonlinear Finite Element Analysis Using ATENA 3D

Fig. 5 summarizes the compression, tension, and shear transfer models implemented in the ATENA 3D software package. In the compression model, the compression hardening function is defined using an elliptical relation through the following Equation 1 [14]–[15]. Beyond the peak, the softening relation is determined through an analogical model commonly known as the crush band model (to ensure mesh objectivity). The assumption was made on the localization of post-peak compressive stress and energy dissipation in a plane normal to the direction of principal stress. A wd value of 0.5 mm was used in this study, following the recommended value for normal concrete [16]. In the tension model, the exponential softening law was adopted following the formulation of a fictitious crack model based on the crack-opening law and fracture energy, as expressed in Equation 2 [14].

$$\frac{\sigma_c}{f'_c} = f_{co} + (f'_c - f_{co})\sqrt{\left(1 - \frac{\varepsilon_c - \varepsilon_c^p}{\varepsilon_c}\right)^2} \tag{1}$$

where σ_c is the normal compressive stress (MPa), f'_c is the mean cylinder compressive strength (MPa), f_{co} is the compressive stress at the post-elastic point (MPa), ε_c is the concrete strain (mm/mm), and ε_c^p is the plastic strain at the peak point (mm/mm).

$$\frac{\sigma_t}{f_t} = \left(1 + \left(c_1\frac{w}{w_c}\right)^3\right) exp\left(-c_2\frac{w}{w_c}\right) - \frac{w}{w_c}(1 + c_1^3)exp(-c_2) \tag{2}$$

where σ_t is the normal tensile stress (MPa), f_t is the tensile cracking strength (MPa), w is the crack opening (mm), and w_c is the crack opening at the complete release of stress deriving from fracture energy (mm). Empirical constants c_1=3 and c_2=6.93 are considered.

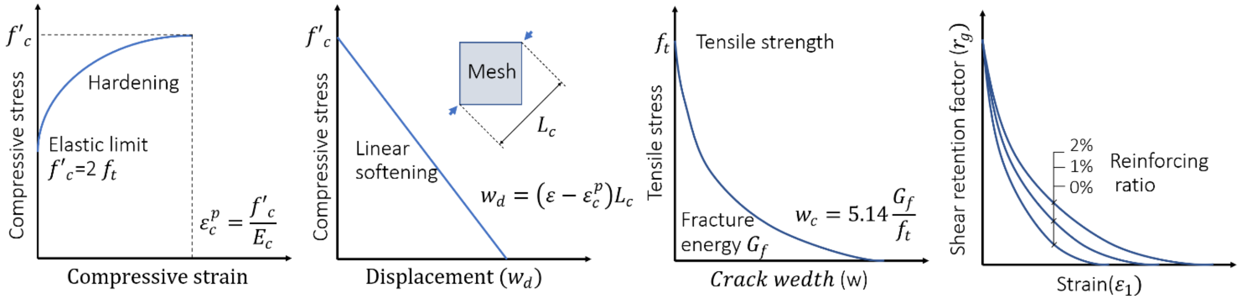

Fig. 5: Compression, tension, and transfer implemented models in the ATENA 3D software package.

3. Results

In this section, the load-deflection curve of the pre-tensioned prestressed concrete beam obtained from ATENA 3D is compared with the experimental results. Fig. 6 illustrates the relationship between the load and deflection of the beam obtained from the laboratory experiment and the numerical modeling. After the yielding of the strands, the beam reached failure, as confirmed in Fig. 7. In other words, the failure type is flexural such that the beam reached failure by the crushing of the concrete long after the yielding of the strands in the beam's mid-span. The ultimate loads were 552.69 kN and 552.80 kN, and the corresponding mid-span deflections were 32.93 cm and 33.52 cm for the laboratory experiment and FE model, respectively.

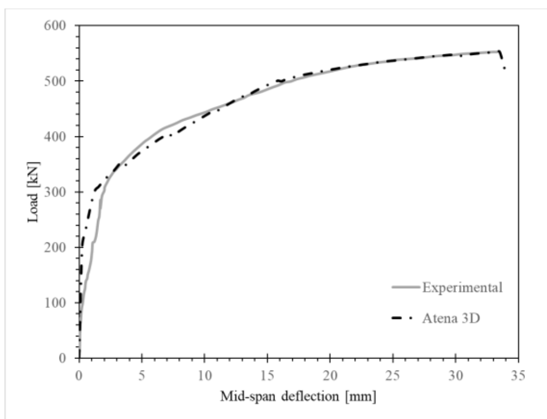

Fig. 6: Experimental and FE results of the four-point static bending test.

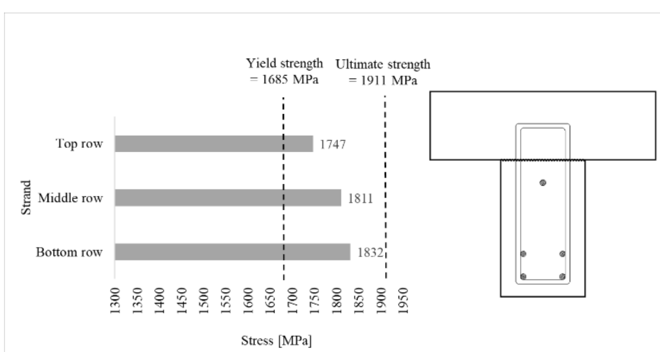

Fig. 7: Stresses along the strands of the beam at failure.

Fig. 8 presents the crack pattern of the beam obtained from the FE analysis and laboratory experiment at the failure. ATENA 3D supports the realistic visualization of cracks and cracking patterns in all stages of the nonlinear analysis. deflection and maximum crack widths were recorded with the gradual increase of the force until failure, as shown in Flexural cracking occurred in the high-moment region of the test specimens when the stresses in the bottom fibers values normally associated with the tensile strength of the concrete. The development of vertical cracks to a height the lower and upper strands characterized the flexural cracking. Flexural-shear cracking followed flexural cracking in the shear-span region of the test specimen. A flexural-shear crack is different from a diagonal crack in that a diagonal crack is caused by primary tensile stresses that develop in the web of an I-beam or the stem of a T-beam.

The nonlinear FE analyses showed strong agreements on the overall load-deflections and failure modes of the beams tested, validating the experimental results.

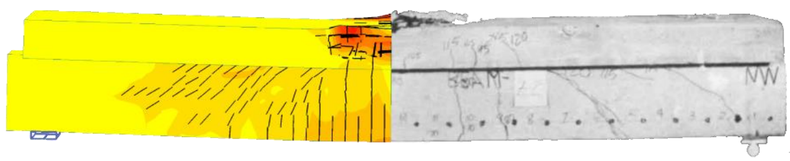

Fig. 8: Comparison of the crack pattern of the beam with the laboratory experiment.

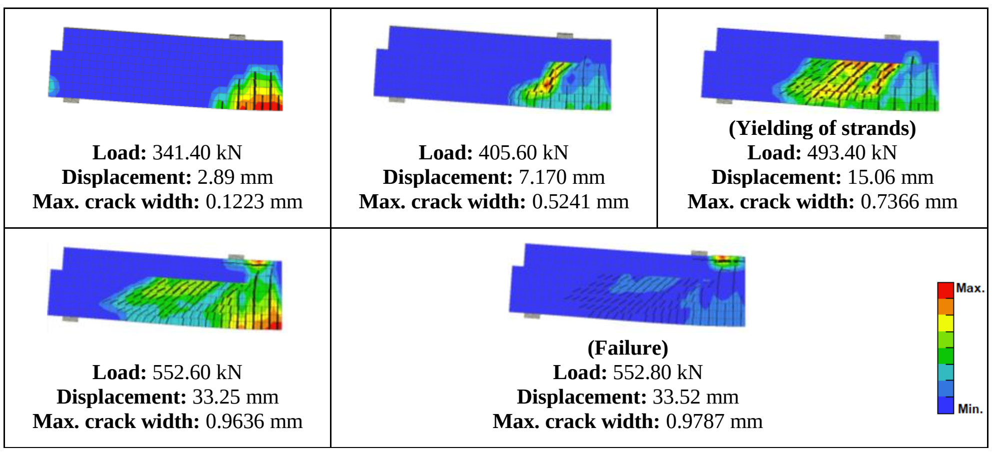

Fig. 9: Crack pattern, maximum crack width, and maximum mid-span deflection of the beam at selected key stages of loading.

4. Conclusion

The four-point static bending test of a prestressed T-beam with three layers of strands was simulated with a nonlinear FE analysis using ATENA 3D in this study, and the results were compared with existing experimental results to validate the model. The specimen was a rectangular prestressed concrete beam with a cast-in-place slab with cylindric concrete compressive strengths of 41.16 MPa and 46.56 MPa at the test, respectively. In this study, the reinforcing steel was seven-wire strands as a longitudinal reinforcement and deformed bars as a transverse reinforcement. The arrangement of shear reinforcement was Φ10@152.4 mm. After examining the analyses, the following points are put forward:

- The failure mode of the beam exhibited an expected mode of failure, which was flexure characterized by strand yielding and eventual concrete crushing. This behavior is desired by structural designers because it provides ample notice before failure occurs.
- The experimental specimen and FE model results were nearly identical in terms of failure mode, crack pattern, ultimate load, and corresponding mid-span deflection, with a variation of less than 2%, which ATENA 3D software express the real behavior.

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