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Drop-weight tests of concrete beams prestressed with unbonded tendons and meso-scale simulation

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ABSTRACT

Impact tests are conducted on concrete beams prestressed with unbonded tendons using a drop-weight facility. These beams are measured comprehensively, including impact load–deformation histories, concrete and tendon strains, and beam cracking process. The interactions between the concrete beam and the tendons are thus systematically analyzed. A model that couples particle elements with finite difference approach (PEM–FDM) is also proposed to simulate the impact behavior of the complete system that is composed of concrete–tendon composites and the loading facility. The comparisons of the test results with those of numerical simulation are satisfactory in terms of load–deformation, concrete and tendon strains, and energy transference among different components. Thus, the main features of the rupture mechanism in structures, including the development of concrete cracking and the yielding effects of tendons, can be reasonably modeled using the PEM–FDM coupling technique.

1. Introduction

Prestressed concrete with unbonded tendons is commonly used in large span structures such as bridges, plants, and aqueducts. The unbonded tendon is attached to the concrete only at the anchorages; thus, the deformation compatibility of the entire structure system must be considered in the analysis of members, that is, member-dependent analysis. Loading behaviors have been studied experimentally and analytically [1–4], particularly the stresses at the ultimate state [5–8] of concrete beams prestressed with unbonded tendons. Fiber-reinforced polymer (FRP) tendons have also been used recently owing to their high strength and corrosion resistance [9,10]. These studies have significantly advanced the design and analysis procedures of prestressed concrete structures.

Although prestressed concrete structures are usually designed for durability, structural performance under dynamic loadings is a concern. Several experimental studies have been conducted on the seismic response of precast unbonded concrete columns [11–13]; nonetheless, little research has focused on the impact behavior of prestressed beams.

In the current investigation, unbonded prestressed concrete beams are systematically tested using a drop-weight facility. Two reinforcement ratios are adopted to obtain the different yielding statuses of the tendons in the tests. Various factors are addressed, i.e., the interaction behaviors between concrete and tendons, rate effects, and residual load capacities in multiple impacts. The overall load–deflection histories and fracture profiles of the concrete beams are recorded and analyzed.

A meso-scale particle element model (PEM) was proposed in the previous work presented by the authors [14–16] and was confirmed to be a powerful tool for analyzing the dynamic behavior of plain concrete. A coupled analytical method is presented in the current study for the drop-weight tests of concrete beams; this method is based on the numerical model of the complete system [17]. The meso-scale PEM is used for concrete, whereas finite difference method (FDM) is introduced to analyze steel tendons. Thus, these discontinuum and continuum approaches are coupled and connected at the anchorage points. The experimental test results are supported by those of PEM–FDM coupling simulation with regard to the dynamic behaviors of concrete beams and the interactions with tendons. The coupling model may be used for the dynamic analyses of other composite structures, such as anchor structures in geomechanics engineering.

2. Experimental program

2.1. Specimens and materials

A schematic of the prestressed concrete beam specimen is shown in Fig. 1 along with a typical cross section. All specimens examined in the impact tests are similarly sized at 400 mm × 100 mm × 100 mm. The tendon holes in concrete beams are precast along the length with an eccentricity of 26 mm. Once the concrete beams are set, tendons

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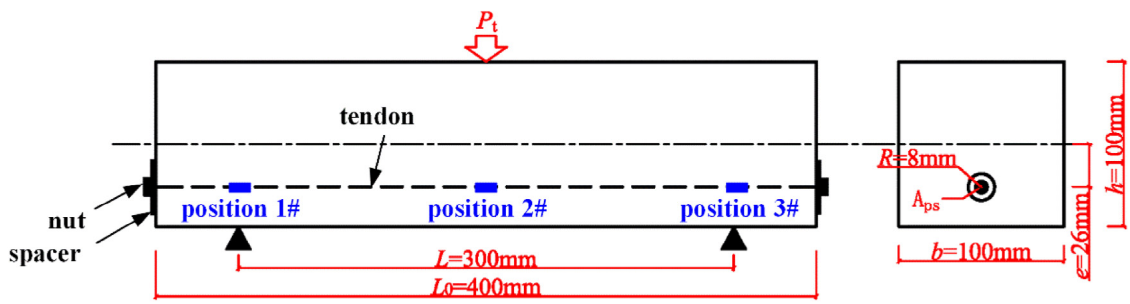

Fig. 1. Dimensions of the prestressed concrete beam specimen.

are screwed at two ends, post-tensioned to a designed level of effective prestress using a hydraulic jack, and anchored to the side walls of the beams.

The proportional design of the concrete mixture (cement:water:fine aggregate:coarse aggregate) is 1:0.43:1.25:2.91. Maximum aggregate size is 20 mm, and mixture density is 2400 kg/m^3. Static compressive tests are conducted on cube specimens measuring 150 mm × 150 mm × 150 mm using a hydraulic servo-machine with a compressive strength of 33.6 MPa and elastic modulus of 36 GPa.

In the tests, two kinds of steel bars are selected as the tendons to perform elastic and plastic (yielding) statuses based on the size of concrete beam and the loading capacity of the drop-weight facility. The mechanical parameters of the tendons are listed in Table 1.

2.2. Test procedures

The drop-weight facility and preparatory tests have been detailed in a previous study for verifying the measurement techniques. The reproducibility has been proved satisfactory and that measurement accuracy can be guaranteed [18]. The measurement system is illustrated in detail in Fig. 2. A 5-kg hammer with an aluminum tup is used in the present investigation. To avoid damage to the transducer surface during impact, an aluminum-alloy pad is glued to the top surface. This pad is replaced for each specimen after impact.

As shown in Fig. 2, the prestressed concrete beam is simply supported on an iron platform with a span of 300 mm. A force transducer and an accelerometer are set on top of the specimen at mid-span to record the impact forces and vertical accelerations, respectively. Four strain gauges are glued to the upper, bottom, and side surfaces of the beam to measure the dynamic strains in the tensile and compressive regions. Gauges are also adhered to the steel bar on three locations, considering that the tendon may exhibit heterogeneity and localized yielding along its length, as depicted in Fig. 1. The strain gauges are also used in the post-tensioning enforcement. To perform elastic and plastic (yielding) statuses of tendons, different effective prestress levels of tendons, f_{pe}, are chosen, and then the corresponding pre-compressing stresses of concrete, σ_p, are measured.

All measurement signals are acquired at intervals of 0.01 ms through a dynamic data collection system. The approach of acceleration–velocity–displacement integration and inertial force calculation are detailed in a previous work [18].

3. Test results and discussion

Simply supported concrete beams prestressed with unbonded tendons are tested using a drop-weight facility. These specimens are divided into three groups, and several parametric issues are studied in each group. In Group 1, beams with different effective prestresses are impacted at a drop height of 2 m. In Group 2, various drop heights ranging from 1 m to 2 m are considered to produce different loading rates. In Group 3, the beams are impacted repeatedly and the residual load capacities are examined. Prestressed concrete beams with different reinforcement ratios are compared with similar plain concrete beams in all three groups.

3.1. Interaction behavior of prestressed concrete and unbonded tendons

Tests are conducted with two different reinforcement ratios to study the interaction behavior of concrete and unbonded tendons. The design parameters are summarized in Table 2. The effective prestresses of tendons f_{pe} are 75 and 166 MPa for specimens with tendons measuring 14 mm in diameter (reinforcement ratio $r = 2\%$). The corresponding prestresses of concrete in the tensile region σ_p are 2.5 and 8.4 MPa, respectively. For the specimens with tendons measuring 8 mm ($r = 0.7\%$), f_{pe} are 245 and 335 MPa. The corresponding $\sigma_p = 1.6$ and 2.5 MPa, respectively. The dynamic interaction behaviors of the prestressed concrete beams and tendons are discussed as follows.

3.1.1. Strain histories of tendons

Fig. 3 shows the dynamic strains ε_{sd} measured by the strain gauges glued onto the tendons. The values reported by the two gauges for tendons with $\Phi = 14$ mm and $r = 2\%$ are close; therefore, these values are averaged and depicted in Fig. 3a. In this study, the tendons experience maximum tensile strains from 0.45 to 1.0 ms and mainly sustain the tension loads. As f_{pe} increases, maximum ε_{sd} decreases. Then, the tendons begin to unload at around 1.0 ms and ε_{sd} reverts to zero. This scenario indicates that the tendons remain elastic during impact. The cracked concrete beams are expected to be re-compressed eventually.

A different pattern of dynamic strains ε_{sd} for tendons with $\Phi = 8$ mm are displayed in Fig. 3b. Given different prestresses, the two gauges on the same tendon generate dissimilar strains in this series of tests; one unloads to a small value around 500 μ, while

Table 1
Parameters of steel tendons.

Steel bar	Diameter Φ/mm	Reinforcement ratio r	Yield strength f_y/MPa	Ultimate strength f_u/MPa	Elastic modulus E_s/GPa
HRB400	14	2%	416	546	200
Q235	8	0.7%	358	577	200