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Flexural behavior of post-tensioned prestressed concrete girders with high-strength strands

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ABSTRACT

Recently, high-strength strands with greater yield and tensile strength than ordinary strands have been developed in several countries. However, the influences of the high-strength strands on flexural members and code provisions have not been fully identified to date. In this study, five large post-tensioned girders were tested to investigate the effect of high-strength strands on the flexural behavior based on the concrete compressive strength and the tensile strength of the strands. The test results indicated that the actual flexural behaviors showed good agreement with the predictions of the current code, regardless of the tensile strength of the strands. The specimens exhibited ductile behavior, and the crack patterns were similar in all the specimens. Certain specimens under service load exhibited crack widths and stress in the tensile reinforcements that slightly exceeded the limit in the current codes. Because the excess was not considerable, reasonable crack control can be achieved by the proper arrangement of deformed rebars. However, further study is required to create clear guidelines.

1. Introduction

For several decades, the tensile strength of prestressing strands in prestressed concrete (PSC) members has remained at 1860 MPa, whereas concrete and reinforcing steel bars have experienced great improvements in strength. Hence, research has focused on the behavior and effect of Grade 1860 strands only [1–9]. Recently, high-strength strands with higher tensile strengths than that of conventional Grade 1860 strands have successfully been developed. Japan developed strands with tensile strengths of 2230 MPa in the early 2000s [10], and several studies in the United States investigated Grade 2069 (300 ksi) strands [11,12]. South Korea also succeeded in developing two grades of high-strength strands, 2160 MPa and 2400 MPa strands, which are increases of approximately 16% and 29% compared with that of conventional Grade 1860 strands, respectively.

With the increase in tensile strength, the yield strength has also increases, whereas other mechanical properties have remained similar to those of Grade 1860 strands. In South Korea, specifications for the mechanical properties of high-strength strands have been created in the recent revision to KS D 7002 [13]. SWPC7CL and SWPC7DL, which are the grade designations for 2160 MPa and 2400 MPa strands, have the same geometric shape, weight, and elastic modulus as those of Grade 1860 strands. Additionally, the same restrictions on the total elongation and relaxation loss are imposed for high-strength strands; the total elongation must be at least 3.5%, and the relaxation loss at 1000 h after tensioning up to 70% of the minimum breaking strength must be below 2.5% for low-relaxation strands. The tests performed by the strand manufacturer in South Korea revealed that the total elongation ranged from 6.00% to 9.48%, and the relaxation loss was between 0.90% and 1.70%.

Because of the increase in the yield and tensile strengths without loss of any other mechanical properties, high-strength strands may have several benefits in PSC members, including reducing the section size, increasing spans of structures, and reducing fabrication costs. However, because experimental results are currently too limited to verify the structural performances of PSC members with high-strength strands, it is necessary that more tests be conducted to investigate whether the current code provisions can be applied for PSC members with high-strength strands or if suitable design guidelines should be established. Therefore, in this study, an experimental program was conducted to investigate the flexural behavior of large-scale post-tensioned PSC girders with high-strength strands. The ultimate capacity and serviceability observed

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Nomenclature

c_2	distance from neutral axis to extreme tension fiber, mm
d	distance from extreme compression fiber to centroid of longitudinal tension rebar, mm
d_p	distance from extreme compression fiber to centroid of prestressing steel, mm
E_c	elastic modulus of concrete, MPa
e	distance from neutral axis to centroid of prestressing steel, mm
f_{ci}	compressive stress of concrete at prestressing, MPa
f'_c	specified compressive stress of concrete, MPa
f_{cr}	modulus of rupture, MPa
f_{cu}	compressive stress of concrete at test, MPa
f_{pi}	initial prestress, MPa
f_{pj}	stress in prestressing steel due to jacking force, MPa
$f_{ps,ACI}$	stress in bonded prestressing steel at nominal flexural strength, MPa
f_{pu}	nominal tensile strength of strand, MPa
$f_{pu,mea}$	measured breaking strength of strand, MPa
f_s	stress in reinforcing steel bar at service load, MPa
f_{se}	effective prestress, MPa
h	height of section, mm
I_g	moment of inertia of gross section about centroidal axis, mm^4
L	span length, mm
M_{cr}	cracking moment, kN m
$M_{cr,cal}$	theoretical cracking moment at center of specimen, kN m
M_d	moment due to self-weight at center of specimen, kN m
M_{max}	maximum moment measured during test of specimen, kN m
$M_{n,ACI}$	nominal flexural strength calculated complying with ACI 318 code at center of specimen, kN m
P_e	effective prestressing force, kN
P_i	initial prestressing force, kN
$P_{n,ACI}$	applied concentrated load corresponding to $M_{n,ACI}$, kN
r	radius of gyration of gross section, mm
t_{pre}	concrete age at prestressing, day
t_{test}	concrete age at test, day
β_1	factor relating depth of equivalent rectangular compressive stress block to neutral axis depth
γ_p	factor for type of prestressing steel
Δ_{cr}	center deflection at the first flexural cracking, mm
Δ_i	camber, mm
$\Delta_{i,cal}$	theoretical camber, mm
Δ_{max}	maximum center deflection during test of specimen, mm
Δf_{ps}	stress in prestressing steel after decompression at full service load, MPa
ρ_p	prestressing steel ratio
ω	tension rebar index
ω'	compression rebar index

through the tests were compared with several code provisions to evaluate the applicability of the code provisions for high-strength strands.

2. Experimental program

2.1. Test variables

In total, five post-tensioned PSC girders were fabricated and tested. The test variables were the compressive strength of the concrete and the tensile strength of the prestressing strands. The compressive strength of the concrete was considered as a test variable in order to investigate that higher strength of concrete provides more efficient use of high-strength strands. There was a concern that normal strength concrete would not be capable of causing the high-strength strands to yield. Two different design compressive strengths of concrete were considered: 40 MPa and 70 MPa. The former represents normal strength concrete (N-series) conventionally used for PSC girders, and the latter represents high-strength concrete (H-series). Three grades of seven-wire prestressing strands were prepared to fabricate the test specimens. The prestressing strands are referred to as SWPC7BL, SWPC7CL, and SWPC7DL, which were designated as Grade 1860, 2160, and 2400 strands, respectively. With the consideration of the test parameters, each specimen was named accordingly to represent the concrete compressive strength and strand grade, as presented in Table 1. The measured compressive strengths of the concrete and the actual tensile strength of the strands are also summarized in the table. The symbols f_{ci} and f_{cu} represent the average compressive strengths of the concrete measured at the days of prestressing t_{pre} and test t_{test}, respectively. Concretes gained the compressive strengths close to the specified values except the HC specimen. The actual tensile strengths of the strands $f_{pu,mea}$ were obtained from the results of the coupon tests performed by strand manufacturer. Typical stress–strain relationships of Grade 1860 strand and high-strength strands are plotted in Fig. 1.

2.2. Design and fabrication of the test specimens

The cross-section of the girders was designed in compliance with the Korean Highway and Bridge Design Code (KHBDC) [14], which is identical to the design methodology of ACI 318 code [15] for a flexural member. The geometry, which includes the prestressing steel ratio ρ_p of 0.195%, was initially determined based on the ND specimen and kept constant for the other specimens. The ND specimen was considered as a girder of a PSC bridge with a deck slab of 19 m wide. The geometry of the ND specimen was designed to ensure that the PSC bridge with the deck slab and the girders resisted the factored load combinations specified in the design code. In the test program, however, the deck slab was not fabricated due to the cost and time. The absence of the deck slab caused no problems with achieving the purpose of the study. The specimens exhibited sufficient flexural deformations and strengths to evaluate the code provisions regarding flexure. Near both ends of the specimens and the diaphragms, the cross-section gradually becomes rectangular to accommodate the anchorages. A girder length of 20 m was determined to minimize the effect of anchorage slip on the effective prestressing force. Details of the test specimens are illustrated in Fig. 2.

Twelve prestressing strands with a diameter of 15.2 mm were placed in each duct, and two ducts were placed with a parabolic profile. The prestressing force was applied to the specimens approximately 3 weeks after concrete placement; however, the ND specimen was prestressed 1 month after concrete placement. The strands were tensioned up to 81% of the yield strength to achieve a full prestressed condition under a full service load, and the strands in the bottom duct were tensioned before prestressing the other strands. The jacking forces were controlled by the load