Prestress Losses in Concrete Rafters with Openings

Falah Jarass Aied Alkhafaji
Department of Civil Engineering
College of Engineering
University of Baghdad, Iraq
falahgaras@gmail.com

Amer Farouk Izzet
Department of Civil Engineering
College of Engineering
University of Baghdad, Iraq
amer.f@coeng.uobaghdad.edu.iq

***Abstract*—In this paper, experimental work was conducted to evaluate the losses in prestressing force of 13 (12 perforated and 1 solid) simply supported prestressed concrete rafters. All beams had the same dimensions and reinforcements. The tested beams were divided into four main groups and three additional subgroups were driven. These groups were classified according to size, number, and configuration of the openings, and the orientation of the posts (vertical or inclined). Regarding the prestress losses that have been affected by the cross-section properties, the provision of the codes is applicable only to prismatic solid beams, so non-prismatic or moreover perforated beams also need to be studied. This paper aims to propose a method based on the same code provisions but taking into consideration the cross-section variation along the beam length. The proposed method divides the overall length of the rafter into a number of assumed prismatic segments with heights measured at centers. Then, the overall prestress loss is found as the sum of these segments weighed by the ratios of the length of each beam segment to the overall length. The experimental results of the proposed method ranged from 84.749% to 95.607% denoting its validity.**

Keywords-prestress losses; rafter beams; openings

I. INTRODUCTION

The stresses in the tendons of prestressed concrete members are decreasing with time, but at a decreasing rate, and asymptotically level off after a long time. The total stress reduction during the lifespan of the member is called total prestress loss [1-3]. The reduction in the prestressing force can be grouped into two categories:

- Immediate elastic loss during the fabrication or construction process, including elastic shortening of the concrete, anchorage losses, and frictional losses.
- Time-dependent losses such as creep, shrinkage, and those due to temperature effects and steel relaxation, all of which are determinable at the service-load limit state of stress in the prestressed concrete element.

An exact determination of the magnitude of these losses, particularly the time-dependent ones, is not feasible, since they depend on many interrelated factors. Empirical methods of estimating losses differ with the different codes of practice or recommendations. The degree of rigor of these methods depends on the approach chosen and the accepted practice of record [4-5].

The presence of openings in gable reinforced concrete beams has many advantages such as flexibility, easier handling, and, most importantly, reduced overall weight. Furthermore, concrete has very low to no maintenance cost and high fire resistance, therefore reinforced concrete gable beams can be used as a good alternative option to design roofs for warehouses, industrial buildings, and airplane hangars instead of steel sections [6-10]. The link structural elements (posts) between the upper and the lower chords of the rafter beam have many advantages such as avoiding Vierendeel truss to prevent shear failure and allowing a beam to enhance its bending capacity and ductility [11]. The fact that concrete is not efficient in resisting tensile stress makes very difficult reaching a long span beam in design, so the addition of prestressing reinforcements has become necessary to reach span lengths which cannot be reached by using ordinary reinforcements [12-13]. To estimate losses such as elastic shortening, creep, shrinkage, and relaxation in beams, the empirical methods recommended by the codes are only applicable to prismatic beams. No special recommendations have been included regarding rafter beams with or without openings. This study has proposed a method to estimate prestress losses in rafter beams, which are divided into a number of segments that are assumed to be prismatic along their lengths with heights measured at centers.

II. EXPERIMENTAL INVESTIGATION

The experimental program consisted of casting and testing of 13 rafter beams, including 12 beams with openings (perforated) and one reference solid beam without openings. All the tested beams had the same rafter geometry, i.e. a rectangular cross-section of 100mm width and height of 400mm at center tapered to 250mm at the two ends, while the overall length was 3000mm with a clear span of 2800mm. Figure 1 shows the geometrical details of the tested beams. Figures 2 and 3 exhibit the details of the solid prestressed rafter concrete beam and the beams with openings respectively. Mild steel reinforcement of 4, 6, and 12mm bar diameters were used while seven-wire low-relaxation strands, Grade 270 with Ø12.7mm diameter were used as prestressing steel. The tested beams were divided into four main groups (A, B, C, and D). These groups were classified according to the studied variables which are: size, openings number, posts inclination, and configuration of the openings. Table I exhibits the grouping according to these variables as follows:

Corresponding author: Falah Jarass Aied Alkhafaji

- Main groups

To study the effect of openings' width versus the number of openings along the beam length, it is worth to highlight that Group A and B had vertical posts whereas Group C had inclined posts. Group A and C had the same upper and lower chords depth of 100mm whereas it was 75mm for Group B. Group D has been prepared in order to study the effect of the increasing of the opening area in the case of using the same number of circular openings.

- Subgroups

Group E has been driven to investigate the effect of increasing opening height or in other words decreasing depth of the upper and lower chords of the beam (beams have been taken from Groups A and B). Group F was driven to find the effect of post configurations linked between the upper and lower beam chords, i.e. the geometric shape of the quadratic openings (beams have been adopted from Groups A and C). Group G consists of beams with the same number of openings but with different openings configurations in order to compare circular and quadratic openings (beams have been chosen from Groups A, B, C and D).

A. Measurements of Prestress Losses

Prestress losses were determined at different stages (at transfer of prestressing force and just before loading test). A special high accuracy electrical resistance measuring device was used for this purpose. Electrical resistance strain gauges (FLA-6-11, length=6mm) with gauge factor of 2.09±1%, and resistance of 120.4Ω were fixed on the strand and bridged to the data logger. An initial reading was recorded on applying the prestressing force, and another reading was conducted before the load test. The electrical resistance is converted to strain through the following equation:

$$\varepsilon = \frac{R_0 - R_i}{kR_0} \qquad (1)$$

where *Ro*=initial electrical resistance at the moment of prestress transfer, *Ri*=electrical resistance immediately before testing, and *K*=strain gauge factor (for this type of strain gauge, *K*=2.09). Through (1) the electrical resistance is converted to strain. This strain is compared with the strain calculated from the elongation which was measured immediately after applying the prestressing [14].

B. Prestressing Process

For post-tensioning concrete gable beams, after attaining the age of 57 days for concrete, the prestressing process has been done according to the following sequence:

- After fixing the strain gauges on the strand (7-wire strand, 12.7mm diameter), it was inserted through the PVC duct which has been embedded in the mold before concrete casting.
- Bridging the strain gauges wires to strain indicator (data logger)
- Attaching the predesigned end bearing steel plates with adequate grips at the beam ends.
- Applying the prestressing force (110kN) from one end according to the ACI-318M-14 [15] limitations.
- Finally, releasing the jack and measuring the strand elongation and the strain which has been occurred in the strand. The corresponding strain was monitored and compared with the reading of the pressure gauge of the hydraulic jack.

TABLE I. DETAILS OF TESTED BEAMS

Group	Beam mark	Shape of openings	Number of openings	Total area of openings (mm^2)	Width of openings (mm)	Height of upper chord (mm)	Height of lower chord (mm)
A	PGB	------	------	0	------	------	------
	PGT6	Trapezoidal	6	180000	200	100	100
	PGT8	Trapezoidal	8	174000	150	100	100
	PGT10	Trapezoidal	10	144000	100	100	100
B	PGB	------	------	0	------	------	------
	PGTH6	Trapezoidal	6	240000	200	75	75
	PGTH8	Trapezoidal	8	234000	150	75	75
	PGTH10	Trapezoidal	10	195000	100	75	75
C	PGB	------	------	0	------	------	------
	PGP6	Trapezoidal with inclined posts	6	154000	200	100	100
	PGP8	Trapezoidal with inclined posts	8	151000	150	100	100
	PGP10	Trapezoidal with inclined posts	10	138000	100	100	100
D	PGB	------	------	0	------	------	------
	PGC1	Circular	8	184200	D	75	75
	PGC2	Circular	8	128000	0.83D	100	100
	PGC3	Circular	8	82000	0.67D	120	120

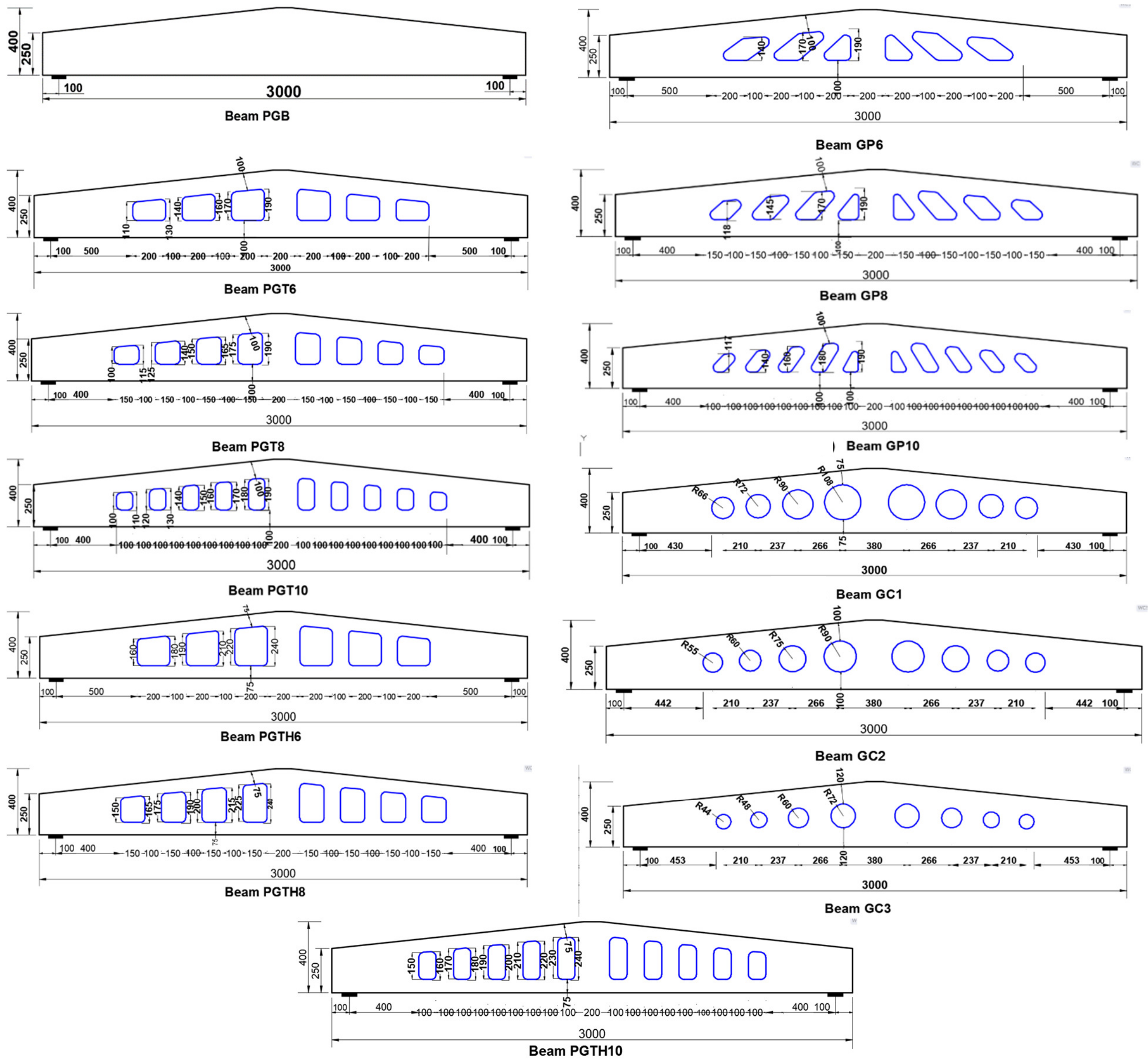


Fig. 1. Geometrical details of the tested beams

III. EXPERIMENTAL RESULTS AND DISCUSSION

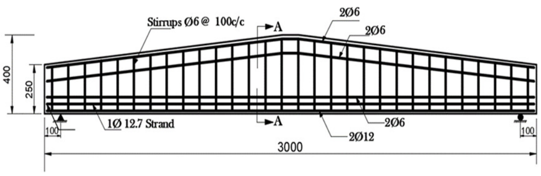
The prestressing losses were monitored. These losses result from end anchorage slip, strand friction with the duct, strand relaxation and shrinkage, and creep of concrete. Table II shows the prestress losses and the residual prestress (effective prestress). It was observed that the losses ranged from 17.465% to 20.309% of the initial prestress depending on size, number of openings, posts inclination, and openings configuration.

The effect of the considered parameters on the prestress losses are: For Group A, B, and C, when the number of openings increases, the prestress losses decrease. This might be due to the minimization of total area of openings and increasing number of posts which have a positive effect on prestress losses and the behavior of the beam in general. The following comparison demonstrates the decreasing ratio in prestress losses with increasing number of openings:

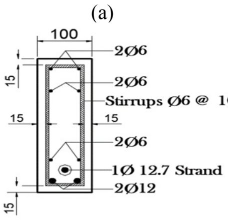
- Group A: 2.558 and 4.33% for PGT8 and PGT10 beams respectively in relation to beam PGT6.
- Group B: 2.175 and 3.403% for PGTH8 and PGTH10 beams respectively in relation to beam PGTH6.
- Group C: 2.888 and 4.764% for PGP8 and PGP10 beams respectively in relation to beam PGP6.
- Group D (circular openings) it can be noticed that, the prestress losses decrease with reducing size of circular openings. The decreasing ratio was 4.25% and 6.441% for GC2 and GC3 beams respectively in relation to GC1.
- Group E compares the beams of Groups A and B. The decreasing depth of both upper and lower chords (Group B) by 25% (elative to that of Group A) led to reduced prestress losses by 3.824% for beam PGT6 related to beam PGTH6 (Group EI), 4.201% for beam PGT8 related to beam

PGTH8 (Group EII), and 4.749% for beam PGT10 related to beam PGTH10 (Group EIII) respectively.

- Group F consists of a comparison between the beams of Groups A and C. The beams of the two groups have the same number of openings and post dimensions but they differ in their inclinations. The prestress losses were 0.438% for beam PGP6 related to beam PGT6 (Group FI), 0.775% for beam PGP8 related to beam PGT8 (Group FII), and 6.567% for beam PGP10 related to beam PGT10 (Group FIII).

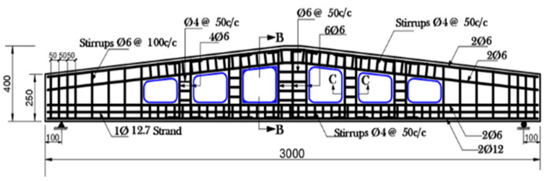


(a)

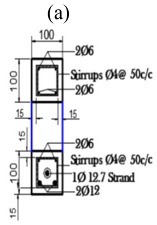


(b)

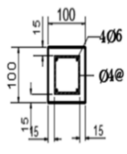
Fig. 2. (a) Reinforcement details for solid rafter PGB, (b) section A-A (all dimensions are in mm)



(a)



(b)



(c)

Fig. 3. (a) Details of reinforcement for rafter with openings PGT6, (b) section B-B, (c) section C-C

- Group G consists of beams having eight openings but different configurations (circular and quadratic openings), with both opening shapes are restricted by the same chord depth. The results indicate a decrease in the prestress losses on the beams with circular openings in comparison with the beams with quadratic openings. The decrease ratios are: 2.488% for beam PGC2 related to beam PGT8 (Group GI), 2.437% for beam PGC1 related to beam PGTH8 (Group GII), and 1.726% for beam PGC2 related to beam PGP8 (Group GIII).

IV. PRESTRESS LOSSES WITH THE PROPOSED METHOD

The variation in cross-section properties should be considered in order to calculate the prestress losses in solid or perforated rafter beams. The method suggests dividing a rafter beam into a set of segments that are considered as prismatic parts with heights measured at centers (Figure 4). For the perforated beams, the number of segments should be chosen in a manner such that the segment is either solid or with openings. The overall prestress loss is found as the summation of the contributions of the beam subdivisions weighed by the ratio of the length of the beam segment to the overall length. The PGT6 beam has been taken as an example to show the steps of the estimation process in details. The same procedure was used for the other tested beams.

1) Instantaneous Losses

a) Anchorage Seating Loss

Usually long tendons will be less affected by seating loss. For short tendons, the seating loss should be detected and subtracted from the applied prestressing force [16]. Assuming ΔA=1.5 mm and L=3000 mm and by (2):

$$\Delta f_{PA} = \frac{\Delta_A}{L} E_P \quad (2)$$

substituting we get Δf_{PA}=98.75MPa.

b) Elastic Shortening

No elastic shortening occurred because only one strand was used in each beam: $\Delta f_{ES} = 0$

c) Friction Losses

The strand is straight therefore there is no curvature, α=0. Assuming that wobble coefficient k=0.002, by (3) we get:

$$\Delta f_{PF} = f_{pi}(\mu\,\alpha + k\,L) \quad (3)$$

substituting we get: Δf_{PF}=6.25MPa. The stress remaining in the restressing strand after all instantaneous stresses is:

$$f_{pi} = f_{pj} - (\Delta f_{PA} + \Delta f_{ES} + \Delta f_{PF}) \quad (4)$$

substituting we get: f_{pi}=116-(105.8+6.25)=1003.95Mpa. The net prestressing force is calculated by:

$$P_i = f_{pi}\,A_{ps} \quad (5)$$

substituting we get: $P_i = f_{pi}\,A_{ps}$=99391N.

2) Time Dependent Losses

a) Stage (I): Losses After 24hr of the Force Transfer

- Relaxation loss:

For t_1=1hr, t_2=24hr:

$$\Delta f_{PR} = f_{pi}\left(\frac{\log t_2 - \log t_1}{10}\right)\left(\frac{f_{pi}}{f_{py}} - 0.55\right) \quad (6)$$

substituting we get: Δf_{PR}=6.89 MPa.

TABLE II. PRESTRESS LOSSES AND STRESSES IN PRESTRESSED CONCRETE BEAMS UP TO THE MOMENT OF TESTING

Group	Beam's labeling	Prestress stress (MPa)	Age of beam at testing (days)	Age of beam transferred to testing (days)	Instantaneous losses after transfer (MPa)	Time dependent losses at testing (MPa)	Total prestress losses, (MPa) ΔPFT	Residual prestress in strands, (effective prestress) (MPa)	Presstress loss/initial prestress (%)	Increasing ratio of losses% (1)
Main groups										
A	PGB	1116	105	48	100.313	94.596	194.909	921.090	17.465	0
	PGT6	1116	115	58	107.088	110.894	217.982	898.0176	19.533	11.837
	PGT8	1116	120	63	105.494	106.912	212.406	903.594	19.033	8.9766
	PGT10	1116	122	65	104.751	103.787	208.538	907.462	18.686	6.9922
B	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGTH6	1116	123	66	105.122	121.528	226.650	889.350	20.309	16.284
	PGTH8	1116	125	68	104.244	117.476	221.720	894.280	19.867	13.755
	PGTH10	1116	127	70	105.208	113.729	218.936	897.063	19.618	12.327
C	PGB	1116	105	48	100.313	94.596	194.909	921.090	17.465	0
	PGP6	1116	128	71	101.489	115.539	217.028	898.972	19.447	11.348
	PGP8	1116	129	72	97.996	112.764	210.760	905.240	18.885	8.1322
	PGP10	1116	130	73	105.789	100.899	206.688	909.312	18.520	6.0427
D	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGC1	1116	131	74	98.013	118.303	216.316	899.684	19.383	10.982
	PGC2	1116	132	75	97.727	109.396	207.123	908.878	18.559	6.2657
	PGC3	1116	133	76	103.649	98.733	202.382	913.618	18.135	3.8338
Secondary groups										
EI	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT6	1116	115	58	107.088	110.894	217.982	898.018	19.533	11.837
	PGTH6	1116	123	66	105.122	121.528	226.650	889.350	20.309	16.284
EII	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT8	1116	120	63	105.494	106.912	212.406	903.593	19.033	8.9766
	PGTH8	1116	125	68	104.244	117.476	221.720	894.240	19.867	13.755
EIII	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT10	1116	122	65	104.751	103.787	208.538	907.462	18.686	6.992
	PGTH10	1116	127	70	105.207	113.729	218.937	897.063	19.618	12.327
FI	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT6	1116	115	58	107.088	110.894	217.982	898.018	19.533	11.837
	PGP6	1116	128	71	101.489	115.539	217.027	898.973	19.447	11.348
FII	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT8	1116	120	63	105.494	106.912	212.406	903.594	19.033	8.977
	PGP8	1116	129	72	97.997	112.764	210.761	905.240	18.885	8.132
FIII	PGB	1116	105	48	100.313	94.596	194.909	921.091	17.465	0
	PGT10	1116	122	65	104.751	116.464	221.215	894.785	19.822	6.640
	PGP10	1116	130	73	105.789	100.899	206.688	909.312	18.520	6.043
GI	PGB	1116	105	48	100.3134	94.596	194.9094	921.0906	17.465	0
	PGT8	1116	120	63	105.4942	106.912	212.4062	903.5938	19.0328	8.9766
	PGC2	1116	132	75	97.72652	109.396	207.1225	908.8775	18.5594	6.2657
GII	PGB	1116	105	48	100.3134	94.596	194.9094	921.0906	17.465	0
	PGTH8	1116	125	68	104.244	117.476	221.72	894.28	19.8674	13.755
	PGC1	1116	131	74	98.01274	118.303	216.3157	899.6843	19.3831	10.982
GIII	PGB	1116	105	48	100.3134	94.596	194.9094	921.0906	17.465	0
	PGP8	1116	129	72	97.99647	112.764	210.7605	905.2395	18.8853	8.1322
	PGC2	1116	132	75	97.72652	109.396	207.1225	908.8775	18.5594	6.2657

(1) $\frac{\Delta PFT\ (beam) - \Delta PFT\ (PGB)}{\Delta PFT\ (PGB)} * 100$

- Creep loss: $\Delta f_{CR} = 0$
- Shrinkage loss: $\Delta f_{SH} = 0$
- Tendon stress at the end of Stage I:

$$f_{ps} = f_{pi} - \Delta f_{PR} \quad (7)$$

substituting we get: f_{ps} =997.06MPa.

b) Stage (II): Losses after 58 Days:

- Creep loss: $P_i = f_{pi}\, A_{ps}$= 98.709kN

$$r^2 = \frac{I_C}{A_C} \quad (8)$$

$$f_{csi} = -\frac{P_i}{A_C}\times\left(1+\frac{e_i^2}{r_i^2}\right)+\frac{MD_i\, e_i}{I_C} \quad (9)$$

For part No.1: i=1, l_1=0.6m (length of segment), X_1=0.3m, $Y_1 = \frac{0.15}{1.45}\times 0.3$ =0.031m, H_1=0.25+Y_1=0.281m (height of sectional center of segment), B_1=0.1m (beam width), $A_1=B_1\times H_1$=0.0281m^2 (cross section area of segment), so:

$I_1 = \frac{B_1\times H_1}{12}$ =0.00018497m^2, $r_i^2 = \frac{I_{C1}}{A_{C1}}$ = 0.00658m^2 and $e_1 = \left(\frac{H_1}{2} - Csg\right)$ =0.0905m. Taking as h=0.25m we have:

$w_1 = B_1 \times h \times \Upsilon_c$ =0.6kN/m and w_2=0.0155kN/m. R is: $R = \frac{(V_T - V_{opening}) \times \Upsilon_c}{2}$=0.963kN, and:

$$MD_1 = R \times l_1 - (w_1 \times l_1 \times x_1 + w_2 \times \frac{l_2}{2} \times x_2) = 0.2617$$

$$\dot{f}_{csi} = -\frac{P_1}{A_{c1}} \times \left(1 + \frac{e_1^2}{r_1^2}\right) + \frac{MD_1\, e_1}{Ici} = 7.75769\text{MPa}.$$

With $\dot{f}_{csi} \times \frac{l_i}{L}$=3.103MPa we have:

$$\dot{f}_{cs} = \sum_{i=1}^{n} \dot{f}_{csi} \times \frac{l_i}{L} \quad (10)$$

$$E_c = 4700 \times \sqrt{f'c} \quad (11)$$

$$n = \frac{E_{ps}}{E_c} \quad (12)$$

substituting in (10)-(12) we get: $\dot{f}_{cs}$=7.718MPa, E_C=29725, and n=6.65. For a posttensioned beam: K_{CR}=1.6, so:

$$\Delta f_{PCR} = n\ K_{CR}\ \dot{f}_{cs} \quad (13)$$

substituting we have Δf_{PCR}=82.12MPa. The same steps are repeated for the other segments (portions) of the beam, and then the total prestress loss due to the creep is found after multiplying f_{csi} by L_i/L for all segments as in (10). The calculations are shown in Table III.

- Shrinkage loss:

$$\Delta f_{SHi} = 2.8 \times 10^{-6}\ KSH_i\ \mathrm{E_{psi}}(1 - 0.06\frac{V_i}{S_i})(100 - RH_i) \quad (14)$$

$$\Delta f_{SH} = \sum_{i=1}^{n} \Delta f SH_i \times \frac{li}{L} \quad (15)$$

For i=1, l_1=0.6m, X_1=0.3m, Y_1=31.034mm we get: H_1=281.03mm, B_1=100mm, V_i=28103mm^2, S_i=(B_1+H_1)× 2 =762.069mm^2 (surface area of segment), K_{SH}=0.77, RH=70%, E_{psi}=197500,and:

$$\Delta f SH_1 = 2.8 \times 10 - 6\ KSH_i\ \mathrm{E_{psi}}\left(1 - 0.06\frac{V_i}{S_i}\right)(100 - RH_i) =>$$

$\Delta f SHi$=34.0994, while $\Delta f SH_1 \times \frac{l1}{L}$=13.6397845MPa and

$$\Delta f SH = \sum_{i=1}^{n} \Delta f SH_i \times \frac{li}{L} = 34.48\text{MPa}.$$

The same steps are repeated for the other segments of the beam, and then the total prestress loss due to shrinkage is the cumulative summarization of the $\Delta f SH_i$ multiplied by L_i/L for all parts as in (15). The calculations are shown in Table IV.

c) Relaxation Loss after 43 Days

f_{ps}=997.06Mpa, t_1=24hr, t_2=1032hr, and

$\Delta \mathrm{f_{PR}} = f_{pi}\left(\frac{\log t_2 - \log t_1}{10}\right)\left(\frac{f_{pi}}{f_{py}} - 0.55\right)$=8.02MPa. The total losses are: $\Delta PFT = \Delta f PCR + \Delta f SH + \Delta f PR$=124.622MPa

$$f_{pe} = f_{ps} - \Delta PFT = 872.438\text{MPa}$$

The same calculations are repeated for all beams. Table V. shows the prestress losses by the proposed method and stresses in prestressed openings. For simplification reasons, the equivalent trapezoidal shape has the same area as the original opening and uniform posts are considered. The same simplification is used for Group D, where equivalent rectangulars are positioned.

TABLE III. CALCULATION STEPS OF CREEP LOSS FOR BEAM PGT6 (ALL DIMENSIONS ARE IN m)

Part No.	i	l_i	X_i	Y_i	H_i	B_i	A_{ci}	I_{ci}	r^2_i	e_i	p_i	MD_i	$\dot{f}_{csi}$	$\dot{f}_{csi}$×l/L
1	1	0.6	0.3	0.031	0.281	0.1	0.0281	0.00018497	0.00658	0.0905	98.71	0.2597	7.75769	3.103
2	2	0.2	0.7	0.072	0.2	0.1	0.02	6.6667E-05	0.00333	0.05	98.71	0.5167	8.24952	1.1
3	3	0.1	0.85	0.088	0.338	0.1	0.0338	0.00032159	0.00952	0.119	98.71	0.585	7.04862	0.47
4	4	0.2	1	0.103	0.2	0.1	0.02	6.6667E-05	0.00333	0.05	98.71	0.6408	8.15642	1.087
5	5	0.1	1.15	0.119	0.369	0.1	0.0369	0.00041858	0.01134	0.1345	98.71	0.6849	6.72019	0.448
6	6	0.2	1.3	0.134	0.2	0.1	0.02	6.6667E-05	0.00333	0.05	98.71	0.7131	8.10221	1.080
7	7	0.05	1.425	0.147	0.397	0.1	0.0397	0.00052306	0.01316	0.1487	98.71	0.7134	6.45419	0.215
8	8	0.05	1.475	-	0.4	0.1	0.04	0.00053333	0.01333	0.15	98.71	0.7309	6.42646	0.214
	∑li	1.5											$\dot{f}cs$	7.718

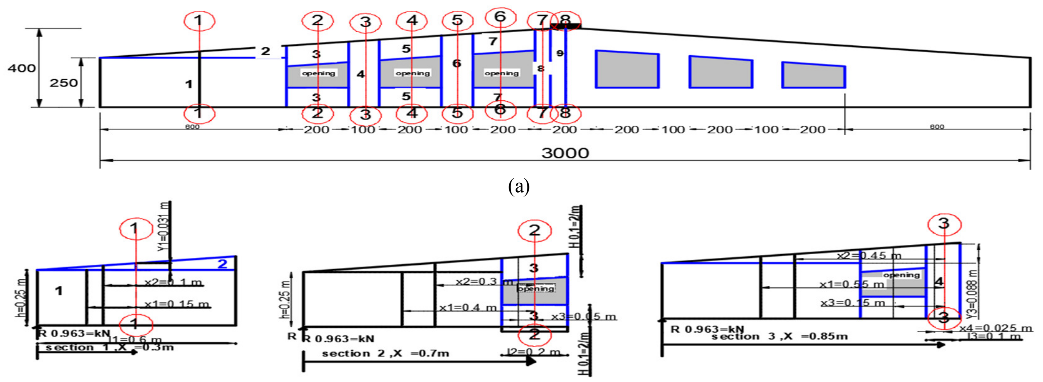


Fig. 4. Dividing the beam to a set of segments. (a) Details and number of segments, (b) section 1-1, (c) section 2-2, (d) section 3-3

TABLE IV. CALCULATION STEPS OF SHRINKAGE LOSS FOR BEAM PGT6 (ALL DIMENSIONS ARE IN m)

Part No.	*l*	X_i	Y_i	H_i	V_i	S_i	*KSH*	E_{ps}	*RH*	ΔfSH_i	$\Delta fSH_i \times L_i/L_{total}$
1	600	300	31.034	281.03	28103	762.069	0.77	197500	70	34.0994	13.639
2	200	700	-	200	20000	800	0.77	197500	70	35.1658	4.688
3	100	850	87.931	337.93	33793	875.862	0.77	197500	70	33.9463	2.263
4	200	1000	-	200	20000	800	0.77	197500	70	35.1658	4.688
5	100	1150	118.97	368.97	36897	937.931	0.77	197500	70	33.8785	2.2585
6	200	1300	-	200	20000	800	0.77	197500	70	35.1658	4.688
7	50	1425	147.41	397.41	39741	994.828	0.77	197500	70	33.8237	1.127
8	50	1475		400	40000	1000	0.77	197500	70	33.819	1.127
$\sum L$	1500									ΔfSH	34.482

TABLE V. PRESTRESS LOSSES BASED ON THE PROPOSED METHOD AND STRESSES IN PRESTRESSED CONCRETE BEAMS UP TO THE MOMENT OF TESTING

Group	Beam	Instantaneous losses (1)			Time dependent losses (2)						ΔPFT (II)	*fps*	*fpe*	ΔPFT (1)+(2)	Prestress loss/initial prestress (%)	Increasing ratio of losses% (1)
					At transfer (I)			At the age of test (II)								
		ΔfPA	ΔfES	ΔfPF	ΔfPR	ΔfCR	ΔfSH	ΔfPR	ΔfCR	ΔfSH						
A	PGB(ref)	98.75	0	6.25	6.89	0	0	7.65	76.47	33.975	118.095	997.06	878.965	229.985	20.608	0
	PGT6	98.75	0	6.25	6.89	0	0	8.02	82.12	34.482	124.622	997.06	872.438	236.512	21.193	2.838
	PGT8	98.75	0	6.25	6.89	0	0	8.18	81.54	34.48	124.2	997.06	872.86	236.09	21.155	2.654
	PGT10	98.75	0	6.25	6.89	0	0	8.25	80.9	34.4	123.55	997.06	873.51	235.44	21.097	2.371
B	PGB(ref)	98.75	0	6.25	6.89	0	0	7.65	76.47	33.975	118.095	997.06	878.965	229.985	20.608	0
	PGTH6	98.75	0	6.25	6.89	0	0	8.28	82.284	34.61	125.174	997.06	871.886	237.064	21.243	3.078
	PGTH8	98.75	0	6.25	6.89	0	0	8.33	81.703	34.609	124.642	997.06	872.418	236.532	21.195	2.846
	PGTH10	98.75	0	6.25	6.89	0	0	8.39	81.028	34.505	123.923	997.06	873.136	235.813	21.130	2.534
C	PGB(ref)	98.75	0	6.25	6.89	0	0	7.65	76.47	33.975	118.09	997.06	878.965	229.985	20.608	0
	PGP6	98.75	0	6.25	6.89	0	0	8.42	81.204	34.43	124.05	997.06	873.006	235.944	21.142	2.591
	PGP8	98.75	0	6.25	6.89	0	0	8.45	80.84	34.43	123.72	997.06	873.34	235.61	21.112	2.445
	PGP10	98.75	0	6.25	6.89	0	0	8.47	80.429	34.169	123.06	997.06	873.992	234.958	21.054	2.162
D	PGB(ref)	98.75	0	6.25	6.89	0	0	7.65	76.47	33.975	118.095	997.06	878.965	229.985	20.608	0
	PGC1	98.75	0	6.25	6.89	0	0	8.5	84.953	34.365	127.818	997.06	869.242	239.708	21.479	4.227
	PGC2	98.75	0	6.25	6.89	0	0	8.53	80.915	34.23	123.675	997.06	873.385	235.565	21.108	2.426
	PGC3	98.75	0	6.25	6.89	0	0	8.55	79.048	34.06	121.658	997.06	875.402	233.548	20.927	1.549

V. COMPARISON BETWEEN THE EXPERIMENTAL AND THE PROPOSED METHOD'S RESULTS

As demonstrated in Table VI, the experimental results converge to the ones of the proposed method. The ratio of experimental to the proposed method's results ranged from 84.749% to 95.607% denoting the validity of the proposed estimation.

TABLE VI. RESULT COMPARISON

Group	Beam	Experimental loss	Proposed loss	Experimental loss / Proposed loss %
A	PGB	194.909	229.985	84.749
	PGT6	217.982	236.512	92.165
	PGT8	212.406	236.09	89.968
	PGT10	208.538	235.44	88.574
B	PGB	194.909	229.985	84.749
	PGTH6	226.650	237.064	95.607
	PGTH8	221.720	236.532	93.738
	PGTH10	218.937	235.81377	92.843
C	PGB	194.909	229.985	84.749
	PGP6	217.028	235.944	91.983
	PGP8	210.760	235.61	89.453
	PGP10	206.688	234.958	87.968
D	PGB	194.909	229.985	84.749
	PGC1	216.316	239.708	90.241
	PGC2	207.123	235.565	87.926
	PGTC3	202.382	233.548	86.656

VI. CONCLUSION

- Increasing the number of quadratic openings along the beam length from 6 to 8 and then to 10 decreased the prestress losses by an average of 2.54% and 4.166%, respectively.
- The prestress losses decrease with reducing size of the circular openings by 17% and 33% from 4.25% to 6.441%.
- Decreasing the depth of both upper and lower chords for perforated beams by 25%, i.e. by increasing openings' height, led to increase prestress losses by an average of 4.258%.
- The average decrease in the prestress losses in beams having inclined posts in comparison with those having vertical ones was 2.593%.
- The average losses decrease in prestressing force for beams with circular openings in comparison with that of quadratic ones was 2.217%.
- The result of the proposed estimated method converges with the experimental results. This accordance ranged from 84.749% to 95.607%.

APPENDIX

A_C	Area of net concrete section
A_{ps}	Area of prestressed steel in tension zone
Ec	Modulus of elasticity of concrete
Eps	Modulus of elasticity of prestressed steel
f_{pi}	Initial prestress stress in prestressed steel
f_{pj}	Stress in prestressed steel at jacking stage
$f'c$	Cylinder concrete compressive strength at 28 days
f_{ps}	Stress in prestressed steel at nominal flexural strength
RH	Relative humidity
I_C	Second moment of area of net concrete section about an axis through its centroid
k	Wobble coefficient
MD	Dead load moment
P_i	Initial prestress force
μ	Curvature friction coefficient
α	Total angular change of prestressing tendon profile in radians from tendon jacking end to any point x
ΔA	Slip in tendon from anchorage
Δf_{PA}	Prestress losses due to anchorage seating
Δf_{ES}	Prestress losses due to elastic shortening
Δf_{PF}	Prestress losses due to friction
Δf_{PR}	Prestress losses due to relaxation

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