Transfer length of high performance pretensioned concrete elements

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Abstract

The scope of this research was to study the feasibility of producing high strength lightweight concrete pretensioned beams, with the same design criteria as normalweight high strength concrete, with 15.2 mm diameter strand. This paper reports an experimental program conducted to measure bond properties of two lightweight concrete dosages compared to those of a reference normal weight high strength concrete, used in a prestressing plant to produce great pretensioned beams. As a part of the research, eight specimens (prisms) were pretensioned with a 15.2 mm diameter strand centered in the cross section, without confinement reinforcement. Experimental results show that none of the prisms cracked right after transfer, which seems to guarantee that adopted strand cover, 45 mm, is enough for lightweight concrete prisms. However, some time after transfer deferred longitudinal cracking was observed in all the lightweight concrete prisms, and a considerable increase of transfer length was detected. Also a new objective method has been developed to determine transfer length from longitudinal concrete strains at strand depth.

Introduction

In pretensioned structures strand force is transmitted to concrete by bond, which is essential:

- To transfer prestress to the beam during the service life. Transfer length is defined as the distance over which the strand should be bonded to the concrete to develop the effective prestress stress in the strand (after ACI318-99).
- To guarantee the anchorage of prestress. A minimum bonded embedment length, called development length, is required for the strand to develop the prestress design stress during the service life.
Prestressing strand bond has been a main subject of research since the late 1950's. In 1963 the actual pretensioning bond formulation was included in ACI standard. By the 1980's Cousins y Johnston [1] measured transfer lengths on 0.5" strands that exceeded ACI assumptions by more than 100%.

Consequently the Federal Highway Administration published a memorandum disallowing the use of 0.6" strand, and imposing severe restrictions on transfer and development lengths of the smaller strands. In 1996 the PCI alerted strand manufacturers of a potential bond problem, recommending to its members the Moustafa bond pull-out test to control strand bond.

During the last years research about bond properties has increased, with the following aims:

- To determine the influence of certain strand and concrete properties, such as concrete strength, strand diameter, fatigue effects on bond, non metallic bonded tendons, epoxy coated strands, ...
- To develop a formulation for transfer and development length, that takes into account the main concrete and strand properties that condition bond.
- To apply analytical and numerical methods to the study of strand bond.
- To develop a standard test to measure prestressed strand bond properties at strand production plants.

PCI manual [2] tabulates lightweight concrete pretensioned beams, prestressed with 0.5" diameter strands, but neither strand cover nor spacing are specified. No reference has been found about production of pretensioned lightweight concrete beams prestressed with 0.6" diameter strand, currently used in Europe for great pretensioned elements.

In 1994 Eurocode part about lightweight aggregate concrete with closed structure [3] was published, as an experimental recommendation. Transfer length for lightweight concrete is determined from a similar resistant normalweight concrete as a function of lightweight concrete specific weight.

**Experimental program**

Eight pretensioned 3750 mm long concrete elements were produced, consisting of 105x105 mm square cross section specimens (prisms), prestressed with a centered strand 15.2 mm nominal diameter (see Figure 1). Strand cover was 45 mm, similar to cover used in current production (42 mm). No confining reinforcement was placed around the strand. Strand was bonded all along the prism. Cross section was designed so that concrete stresses be less than 45% average concrete strength at transfer.

Three concrete dosages were used in these tests: a high-strength normalweight concrete regularly used to produce long pretensioned concrete beams (up to 45 meters), which will be called from now on reference concrete, RC, and two different dosages of lightweight concrete, LC, made from lightweight aggregate expanded clay F-7, from ARLITA ©.

Lightweight concrete performance is very sensitive to initial lightweight
aggregate humidity. Given a concrete workability, total water content depends on initial lightweight aggregate humidity. So two dosages were adjusted, one corresponding to a high aggregate water content (10%, to produce LC10-I concrete) and the other to a low water content (3%, to produce LC3-1 concrete), being their only difference the amount of water added during batching. Concrete dosages are summarized in Table 1 and concrete properties in Table 2.

Table 1: Concrete dosages

<table>
<thead>
<tr>
<th>Mat.</th>
<th>Water</th>
<th>Gravel 12/18 mm</th>
<th>Gravel 6/12</th>
<th>Arlita 1-7</th>
<th>Humidity of Arlita</th>
<th>Sand 0/6</th>
<th>Cement I-52,5R</th>
<th>Plasticizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>184</td>
<td>345</td>
<td>515</td>
<td>-</td>
<td>877</td>
<td>450</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>LC3-1</td>
<td>205</td>
<td>-</td>
<td>550</td>
<td>3</td>
<td>610</td>
<td>500</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>LC10-I</td>
<td>190</td>
<td>-</td>
<td>550</td>
<td>10</td>
<td>610</td>
<td>500</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Summary of the materials properties

<table>
<thead>
<tr>
<th>PROP.</th>
<th>concrete specific weigh</th>
<th>average concrete strength, at 2 days</th>
<th>average splitting tensile strength, at 2 days</th>
<th>average modulus of elasticity, at 2 days</th>
<th>average direct tensile strength, at 2 days</th>
<th>average concrete strength, at 28 days</th>
<th>average direct tensile strength, at 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITS</td>
<td>kN/m³</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>RC</td>
<td>22</td>
<td>50</td>
<td>3.2</td>
<td>30441</td>
<td>3.3</td>
<td>67</td>
<td>&gt;3.3</td>
</tr>
<tr>
<td>LC10-I</td>
<td>17</td>
<td>48</td>
<td>2.7</td>
<td>19939</td>
<td>2.7</td>
<td>56</td>
<td>2.9</td>
</tr>
<tr>
<td>LC3-1</td>
<td>17</td>
<td>49</td>
<td>&gt;2.7</td>
<td>20326</td>
<td>2.6</td>
<td>51</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Strand type was Y1860 S7, 15.2 mm diameter (0.6") from the same lot, tensioned up to 75% of ultimate strength, \( f_{pu} \). Strand surface was slightly rusted, and strand surface was carefully cleaned with acetone before concrete casting.

The concrete batches were produced in our lab using a vertical axis mixer, 100 liter capacity. During casting, concrete was internally vibrated to ensure proper consolidation. Specimens were covered with wet cloths and plastic sheets, until at 20 hours the form was removed.

Instrumentation consisted of Wykeham Farrance detachable mechanical strain gauges placed each 50 mm at both sides at strand depth. Strains were measured at transfer, and at different ages after in order to evaluate transfer length evolution.

Also electronic instrumentation was used. Hollow load cells were placed to measure prestressing at both ends of the pretensioning bench during prestressing process and transfer. Displacement transducers were used to measure strand draw-in at both ends. Several strain gages placed along the strand external wires and along the prism lateral sides at strand depth, to measure longitudinal strains.
Transfer took place 48 hours after concrete batching, after initial strain readings were taken, and was performed heating gradually with an oxygen-propane torch a 50 cm zone at the North end of the prisms. The process was completed in a period of 5 to 15 minutes. During transfer and at 28 days concrete properties were determined testing the specimens cast with the prism.

Figure 1: View of pretensioning bench, hydraulic jack and prism

Analytical procedure to determine transfer length

Three different methods have been traditionally used to evaluate transfer length from concrete strain measures taken along prestressed concrete prism sides. These methods have three things in common: a subjective assessment of the points belonging to the constant strain plateau is made, the strains corresponding to these points are averaged, and this value defines the constant strain plateau (see FHWA94, [4]). Also their common hypothesis is a linear behavior of longitudinal strains along the transfer zone at any age.

- **100% constant strain method.** Transfer length is defined as the minimum distance from the end of the member to a point presenting a strain less than the average constant strain.

- **95% constant strain method.** Transfer length is defined as the minimum distance from the end of the member to a point presenting a strain less than 95% of the average constant strain. In this method a correction of shear lag effect is intended (FHWA94).

- **Slope intercept method.** After the constant strain plateau is delimited, a general straight line is adjusted applying linear regression analysis to strain measures at each transfer zone. Transfer length at each end is determined as the minimum distance from the end of the member to the intersection between each adjusted straight line and the constant strain plateau.

Shear lag affects concrete strain profile at the prism side: transfer length determined through prism side concrete strain measures (apparent transfer...
length) is greater than real transfer length (at strand surface).

To determine the transfer length two methods were developed in this investigation, inspired in slope-intercept method. Experimental concrete strain measures taken along the prism sides at a given time determine a set of "n" points \((x_i, \varepsilon_c(x_i))\), \(i = 1, \ldots, n\) along the prism length. Two theoretical models with laws \((x, \varepsilon_c(x))\) are considered:

- **Linear model results** when concrete is supposed to be cracked around the tendon, so a constant friction coefficient between strand and surrounding concrete is assumed in the transfer zone varies linearly from zero to its effective value along the transfer length. Assuming a linear stress-strain curve, two external generic straight lines result for transfer zones, and a horizontal central line corresponding to the perfect bond zone. Parameters needed to determine the linear profile are (see Figure 2):

  \[m_1, m_2, M, L_{t1}, L_{t2}\]

- **Exponential model** is based on bond differential equation for the following boundaries: perfect confinement of strand by concrete, or elastic confinement of strand exerted by concrete. In this model a generic exponential law is assumed for longitudinal concrete strains at transfer zones, and a central horizontal line for the perfect bond zone. Theoretical laws at transfer zones are:

  \[\varepsilon_c(x) = a_1 + b_1 e^{c_1 x}, a_1, b_1, c_1 \in R, x \leq L_{t1}\]

  \[\varepsilon_c(x) = a_2 + b_2 e^{c_2 x}, a_2, b_2, c_2 \in R, x \leq L - L_{t2}\]
Parameters needed to determine the exponential profile are (see Figure 3):

\[ m_1, m_2, M, L_{i1}, L_{i2}, c_1, c_2 \]

To apply linear or exponential method the determination of parameters is needed to define the strain profile that best adjusts experimental measures strain profile. This process is described herein (see Vázquez, C. [5]):

1. An arbitrary initial theoretical profile, \((x, \varepsilon_c(x))\), is set. Theoretical strains \( \varepsilon_c(x) \) are determined.
2. Quadratic error committed adjusting experimental strain measures with initial theoretical profile is determined:
   \[
   F = \sum_{i=1}^{n} (\varepsilon_c(x_i) - \varepsilon_c(x_i))^2
   \]
3. The purpose is to search the profile, defined by its parameters, that presents the minimum quadratic error (which is the objective function). This is done through an optimization process implemented in VBA for Excel. Process consists of minimization of the objective function, until a convergence criteria is fulfilled \((F < \varepsilon\), being \( \varepsilon \) a prefixed value). At that moment the parameter values define an optimal theoretical profile, and apparent transfer lengths at dead and live ends respectively, \( L_{i1} \) and \( L_{i2} \), are determined.
4. The accuracy of the theoretical profile is defined through the \( R^2 \) value evaluated along each transfer zone. \( R^2 \) is the square of the coefficient of the moment of correlation of the Pearson product of \((x_i, \varepsilon_c(x_i))\) vs. \((x, \varepsilon_c(x))\).

These methods overcome initial subjective determination of the central constant strain plateau, which is one of the main shortcomings of the previously described methods.
Experimental results and discussion

Prestress losses after transfer were 9% for CC, and 11% for LC3-1 and LC10-1, values close to the expected losses. Right after transfer no cracking was observed in any of the concrete prisms. Prisms were observed periodically thoroughly afterwards, to determine if cracks developed. None of the RC prisms has cracked up to the date.

However, some time after transfer (from several days to several weeks) longitudinal cracks at strand depth were observed in all the lightweight concrete prisms. Cracks began at one end and grew slowly (in a process that took several days or weeks) until the prism was cracked all along its length. This happened to all the lightweight concrete prisms.

In Figure 4 and Figure 5 strain profiles at different ages are shown for a RC prism, for linear and exponential method respectively. It can be seen that transfer length at both ends remains constant through time. Total strains increase due to concrete shrinkage and creep.

In Figure 6 and Figure 7 strain profiles at different ages are shown for a LC3-1 lightweight concrete prism. It can be seen that immediately after transfer central perfect bond zone is perfectly shaped and transfer length
values are similar to those of RC. However, after six days transfer lengths increase until central perfect bond zone practically disappears. This increase has been simultaneous to the observed general longitudinal cracking.

Table 3: Minimum and maximum measured transfer lengths (mm)

<table>
<thead>
<tr>
<th>MODEL</th>
<th>RC at transfer</th>
<th>after 1 year</th>
<th>LC3-1 at transfer</th>
<th>after 1 year</th>
<th>LC10-1 at transfer</th>
<th>after 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIN.</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>725</td>
<td>1032</td>
<td>714</td>
<td>1110</td>
<td>743</td>
<td>1008</td>
</tr>
<tr>
<td>EXP.</td>
<td>759</td>
<td>1000</td>
<td>718</td>
<td>1068</td>
<td>828</td>
<td>div</td>
</tr>
</tbody>
</table>

In Table 3 transfer length values, determined by linear and exponential methods, are presented for each prism. Maximum and minimum values for each prism (determined from East and West results for Dead end and Live end) are presented at transfer and one year later. Transfer length at transfer age is similar for the different dosages. However, all the lightweight concrete prisms experienced a considerable increase in transfer length values with time. In some of them both transfer zones got unified, so perfect bond central zone disappeared. As a consequence, these prisms suffered a general loss of prestress, which questions transfer length concept. Average increase of transfer length value with time respect to transfer age value was 8% for CC, and more than 100% for LC3 and LC10.

Figure 6

A comparative analysis was performed to determine which method, linear or exponential fits better the measured strains profile, for both normalweight and lightweight concrete [5]. The following remarks have been stated as a result of this comparative analysis:

I. Linear method provides more approximate transfer length values for East and West side of prisms than exponential method.

II. Exponential method provides higher $R^2$ values in transfer zones.
for lightweight concrete prisms than linear method, which means that transfer zone strain profile fits better an exponential curve than a linear curve.

III. For conventional concrete prisms, linear and exponential method provide similar R² values in transfer zones.

![Graph](image.png)

Figure 7

In our opinion a better understanding of bond process is got performing both linear and exponential proposed analysis. The most favorable bond condition (perfect confinement of strand by concrete) and the most unfavorable condition (concrete cracked around the tendon, only friction stresses) are considered. So we can limit transfer length by upper and lower boundaries. Maximum transfer length is necessary to determine in a safe way the bearing capacity in the transfer zone. Minimum transfer length is necessary to determine the maximum splitting stresses, which makes it possible design of necessary ordinary confinement reinforcement (Model Code CM-90 [6]).

Comparison of results with different formulations

- Transfer length results obtained from this research for RC at any age are limited by minimum transfer length and maximum transfer length values predicted by Model Code [6] formulation (555 and 1109 mm respectively).
- Transfer length predicted by the Eurocode for RC prisms, 838 mm, is very close to the transfer length average value at transfer.
- Transfer length predicted for reference concrete prisms immediately after transfer by ACI318-99, 980 mm, is an upper boundary of RC transfer length results at transfer.
- LC transfer length predicted by Eurocode [3], 959 mm is an upper boundary for the experimental results at transfer. However, this value is doubled one year after transfer for most LC prisms, as a result of LC prisms generalised longitudinal cracking.
Conclusions

1. Adopted strand cover (45 mm) has proved enough for normalweight concrete and insufficient for lightweight concrete. In all the lightweight prisms longitudinal cracking has been observed some days after transfer, and cracks progressed gradually along the whole prism length. For this last material cover does not guarantee transfer of prestress through service life.

2. Two new methods have been developed to estimate transfer length from experimental concrete longitudinal strain measures taken along the prisms sides, at strand depth. Adjust is made through an optimization process, minimizing quadratic error. These methods overcome one of the former methods main shortcomings: the extent of the perfect bond zone is determined in an objective way.

3. Linear and exponential method provide similar and reliable results for prisms transfer length. Linear method provides better results for conventional concrete, but exponential method is not worse than linear method to estimate lightweight concrete transfer length.

4. In our opinion excessive bond between strand and lightweight concrete is the responsible of high bond stresses in transfer zone. These stresses may cause concrete cracking due to: low instantaneous and deferred direct tensile strength of LC, low fracture energy of LC (20-30% less than RC), and reduced transversal ultimate strains of lightweight concrete vs. RC’s.

5. Eurocode transfer length expression has been unsafe for the tested lightweight concrete dosages: average transfer length has increased more than 100% during the first year after transfer. Research must be undertaken to determine specific design rules to prevent pretensioned elements from splitting and from increasing transfer length values. In our opinion deferred lightweight concrete properties must be studied and taken into account in future standards.

References