Graphical tool for development of long-span PSC girder bridges

*Se-Jin Jeon¹⁾, Myoung-Sung Choi²⁾ and Young-Jin Kim³⁾

 ¹⁾ Department of Civil Systems Engineering, Ajou University, Suwon 16499, Korea
 ²⁾ Department of Safety Engineering, Dongguk University, Gyeongju 780-714, Korea
 ³⁾Civil Engineering Research Team, Daewoo E&C, Institute of Construction Technology, Suwon 16297, Korea
 ¹⁾conc@ajou.ac.kr

ABSTRACT

Although the prestressed concrete (PSC) girder bridge is known to be more economical than other types of bridges in short and medium spans, a longer span has also been achieved by applying several strategies. This paper presents a systematic procedure that can be used to assess the effects of these strategies on the span. The proposed scheme adopts a graphical approach that represents a relationship between the number of prestressing tendons and the span and is derived on the basis of stress assessment equations of the girder at each stage of fabrication and in service. A quantitative evaluation for the extension of the span is performed by adopting a sample bridge. A number of advantages of the proposed scheme are apparently shown for determining why and how each strategy contributes to the span extension and for suggesting further improvement for a longer span. The results imply that increasing the strength of the girder, making the girders continuous, multistage prestressing, and the decked PSC girder are very effective.

1. INTRODUCTION

In the United States, prestressed concrete (PSC) girders have been used primarily in spans of less than 45 m (Meir et al. 1997) and, in Korea, in spans of 25-35 m for highway bridges owing to their economic efficiency for these short and medium spans. Since the 1980s in the United States and Canada, longer-spanned PSC girders have also been used to replace conventional steel bridges that have a high material cost. For example, the AASHTO Type I-IV girders, which had been developed in the United States in the 1950s-1960s, were upgraded to the AASHTO-Precast/Prestressed Concrete Institute (PCI) Bulb-Tee girders and to other girder sections specific in each

¹⁾ Associate Professor

²⁾ Assistant Professor

³⁾ Research Fellow

state of the United States. Representative examples of the latter are the University of Nebraska (NU) Bulb-Tee girder (PCI 2003), which achieved a 65-m span with a 2.8-m girder height, and the New England Bulb-Tee (NEBT) girder (Bardow et al. 1997). On the other hand, in Korea, new types of longer-spanned PSC girders of up to 50 m that adopt the multistage prestressing technique have been developed and used in practice since the 2000s. To extend the conventional span ranges of the PSC girders to longer than 50 m, it would be particularly important to maintain economic efficiency, constructability, and aesthetics even for the extended span. Therefore, it would not be a good strategy to simply increase the girder height. A number of techniques have been proposed that can contribute to achieving a longer span with a reasonable girder height from the perspectives of material, design, and construction (Castrodale and White 2004; PCI 2003). The relevant investigations show that combining several strategies in an optimal way is recommended to obtain an efficient long-spanned girder. In this respect, a more systematic approach is required that can explicitly show a relationship between the influencing factors and the span, instead of repetitive and trial-and-error-based designs, to propose optimized long-spanned PSC girders. This approach should also be useful in prioritizing the strategies that are applied to achieve a longer span. In this study, therefore, a graphical approach is proposed that can be used to readily assess the effects of the influencing factors on a span range of the PSC girder bridge. A quantitative evaluation for the span extension is performed for a sample bridge by applying the proposed procedure.

2. STRATEGIES FOR LONGER SPAN

Application of high-strength concrete is the most effective strategy for the longspan PSC girder in terms of material. In the United States, although the most common range of the specified compressive strengths is 34.5-48.3 MPa (Meir et al. 1997), higher strengths are also used. For example, the aforementioned NU Bulb-Tee girder with a 65-m span employed a strength of 60-65 MPa. According to the typical drawings of PSC girders presented by the Korea Expressway Corporation in Korea, the design strength has been fixed as 40 MPa, but the higher strength of 60 MPa is included in the improved typical drawings.

Lightweight aggregate concrete is effective in extending the span in terms of reduced self-weight. Recently in the United States, lightweight concrete has been extensively applied to both the deck and the girder (Liles and Holland 2010).

The span also has a close relationship with the prestressing tendons. It is expected that the required number of tendons increases concurrently with an increase in the span of the PSC girder. This may cause a congestion of tendons or sheaths, resulting in difficulties in the placing work of concrete and in violation of the minimum distance requirement between the tendons, between the sheaths, and even between the anchorages in the case of a post tensioning system. The PSC girders in Korea and Japan adopt the post tensioning system in most cases, whereas in the United States, the pretensioning system is common. Regardless of which system is used, the use of the tendon with a higher strength and a larger diameter is expected to contribute to extending the span by reducing the required number of tendons. The strength of the

tendon most widely used around the world is 1,860 MPa, as specified in ASTM (2006). However, studies to increase the strength up to 2,100-2,400 MPa have continued. Furthermore, there are two representative diameters of the seven-wire strand commonly used: 12.7 and 15.2 mm. Typical PSC girders of the United States, Korea, and Japan use 12.7-mm-diameter seven-wire strand, but it is becoming increasingly more popular to apply a larger diameter of 15.2 mm, especially for long-span PSC girders.

As mentioned previously, an optimization of the section shape has been basically considered when the span is to be extended. In this respect, the Bulb-Tee shape has been generally accepted as more efficient than the conventional I-shaped girder (Bardow et al. 1997; Lavallee and Cadman 2001; Meir et al. 1997; PCI 2003). Compared with the I shape, the Bulb-Tee shape has a wider upper flange and optimized section details. The efficiency of the section can be evaluated by the coefficient of section efficiency (Guyon 1963), as shown in Eq. (1). The economical efficiency affected by the amount of concrete is also represented by the area included in Eq. (1).

$$\rho = \frac{I_c}{A_c y_t y_b} \tag{1}$$

in which I_c = moment of inertia; A_c = area of the section; and y_t and y_b = distances from the neutral axis to the top and bottom fibers of the section, respectively.

In the case of multispan girder bridges, the span can be extended by making a series of simple-span girders continuous in the longitudinal direction. This is possible because of the reduced positive moment within the span in the continuous girder system.

Multistage prestressing is another very effective strategy to extend the span (Han et al. 2003). Two-staged prestressing is normally applied when the girder is fabricated (primary prestressing) and after the self-weight of the deck is applied (secondary prestressing). As will be demonstrated subsequently, the secondary post tensioning can be applied either before or after the cast-in-place deck is hardened, in which the former is more favorable in view of efficiency of the prestressing. Sometimes it is difficult to complete the tensioning work before the cast-in-place deck is hardened. To cope with this problem, the precast concrete deck panel (Issa et al. 2007) may be a useful solution, in which the secondary post tensioning work is conducted before the shear pockets of the precast decks are filled with mortar for composite action.

On the other hand, the decked PSC girder system (Smith et al. 2008) shown in Fig. 1 can also contribute to extending the span. In this system, both the girder and deck are cast simultaneously at a casting yard. The monolithic girders are then transported and erected onto piers or abutments and are integrated together in the transverse direction by shear connectors or prestressing tendons. Originally, the idea to use the decked girder system was introduced to accelerate bridge construction (Cisneros et al. 2008). However, the deck PSC girder can also contribute to span extension by introducing the maximum prestress level that is theoretically possible.



Fig. 1 Decked prestressed concrete girder bridge

In the United States and Canada, precast concrete/PSC spliced girder bridges (Abdel-Karim and Tadros 1992) have been frequently constructed. The girder is divided into a certain number of segments in the longitudinal direction, and the segments are integrated together by, for instance, prestressing tendons penetrating all the segments in the longitudinal direction. The concept was primarily introduced to cope with the weight increase of a long-span girder, which causes some difficulties during transportation and erection.

3. PROPOSED ASSESSMENT PROCEDURE FOR SPAN

3.1 General remarks

The contribution of the aforementioned strategies for extending a span can be identified by adopting a conventional design procedure for a PSC girder bridge and by comparing the results of applying each strategy. However, the trend of the span extension as affected by a single strategy or a combination of strategies cannot be clearly realized through this type of time-consuming trial-and-error method. This may cause some difficulties in prioritizing the design options for extending a span.

To accommodate the design of a long-span PSC girder bridge that meets the target span in an efficient and effective manner by improving the conventional trial-anderror-based procedure, this paper presents a graphical methodology. According to the general procedure of designing a PSC girder bridge, the safety and serviceability are verified by the strength design method and service load design (allowable stress design) method, respectively, and some additional serviceability is then separately verified. For the limit state design, as presented, for instance, in AASHTO (2010), these procedures are included in the verifications of the strength limit state and service limit state. Among the checklists, complying with the allowable stress limits may be a crucial factor to ensure that the PSC girder is free from any harmful cracks or crushing damages. In the proposed procedure, therefore, the stress assessment equations using the allowable stresses are converted to the corresponding graphs representing the relationship between the number of prestressing tendons and the span. By overlapping the graphs thus established, a feasible design domain can be formed, and the possible maximum span range and the contribution of each option to the span extension can be easily identified. Although the proposed procedure is stated assuming a post tensioned girder, which is common in Korea, the methodology can be extended without a great deal of difficulty to a pretensioned girder, which is dominant in the United States, through a

slight modification of the equations.

3.2 Derivation of fundamental equations for graphical assessment

According to the allowable stress design or service limit state design of fully prestressed components (AASHTO 2002; AASHTO 2010), the stresses at the top and bottom fibers should satisfy Eqs. (2)-(5) at the mid span of a girder in each stage (Naaman 2004). In this discussion, the sign convention of the stress is regarded as positive when it is in compression. Eqs. (2) and (3) correspond to the temporary stresses before losses when a girder is initially prestressed, whereas Eqs. (4) and (5) deal with the stresses at service load after losses:

$$f_{ct} = \frac{P_i}{A_c} - \frac{P_i e_p}{I_c} y_t + \frac{M_{d1}}{I_c} y_t > f_{ci,g,ta}$$
(2)

$$f_{cb} = \frac{P_i}{A_c} + \frac{P_i e_p}{I_c} y_b - \frac{M_{d1}}{I_c} y_b < f_{ci,g,ca}$$
(3)

$$f_{ct} = \frac{P_e}{A_c} - \frac{P_e e_p}{I_c} y_t + \frac{M_{d1} + M_{d2}}{I_c} y_t + \frac{M_l}{I_c^*} y_{t,g}^* < f_{c,g,ca}$$
(4)

$$f_{cb} = \frac{P_e}{A_c} + \frac{P_e e_p}{I_c} y_b - \frac{M_{d1} + M_{d2}}{I_c} y_b - \frac{M_l}{I_c^*} y_b^* > f_{c,g,ta}$$
(5)

in which f_{ct} and f_{cb} = top and bottom fiber stresses, respectively; $P_i = nA_{ps}f_{pi}$; and $P_e = nA_{ps}f_{pe}$. Here, *n* is the number of sheaths (ducts), and A_{ps} is the total area of the strands included in one sheath in a post tensioned girder. In the case of a pretensioned girder, these notations should alternatively be interpreted as the number of strands and the area of one strand, respectively. Also, f_{pi} and f_{pe} are the average initial and effective prestress, respectively, and e_p is the average eccentricity of the strands. Although e_p can be slightly changed as n increases, in most cases, however, designers may try to maintain e_p to be as large as possible to increase the efficiency of the prestressing regardless of n. Therefore, it can be identified that the assumption of the single average eccentricity is practically acceptable in most cases. Notations for the subscripts are as follows: An asterisk (*) indicates a composite section of the girder and deck; g is the girder; and ta and ca are the allowable tensile and compressive stresses, respectively. In the AASHTO specifications (2002, 2010), the allowable stresses can be expressed as a function of the compressive strengths of concrete, that is, $f_{ci,g,ta} = a_1 \sqrt{f_{ci,g}}$, $f_{ci,g,ca} = a_2 f_{ci,g}$, $f_{c,g,ta} = a_3 \sqrt{f_{c,g}}$, and $f_{c,g,ca} = a_4 f_{c,g}$, in which, f_{ci} and f_c = specified compressive strengths at the time of prestressing and in service, respectively; M_{d1} = bending moment by the self-weight of a girder; M_{d2} = bending moment by the self-weight of a deck with the contribution of cross beams (diaphragms) included; and M_i = bending moment by live load with the self-weight of pavement and

railing included. The moments can be expressed as follows: $M_{d1} = b_1 w_{d1} l^2 = b_1 (\gamma_c A_c) l^2$, $M_{d2} = b_2 (w_{d2} + w_c) l^2 = b_2 (\gamma_{c,d} A_d + w_c) l^2$, and $M_l = b_3 w_l l^2$, in which γ_c and $\gamma_{c,d}$ = unit weights of the girder and deck, respectively; A_d = area of the deck; l = span; and w_c = equivalent distributed load exerted by cross beams. The equivalent distributed live load w_l applied to one girder can be obtained by finite element analysis of the entire bridge system or by the theory of lateral load distribution. The moment coefficients $(b_1, b_2, and b_3)$, which represent the maximum positive moment occurring in the span, are 0.125 for a simple span and have a lower value for a continuous span. Substituting all the preceding notations for Eqs. (2)-(5), the equations can be transformed to Eqs. (6)-(9), respectively:

$$l > \sqrt{\frac{I_c}{b_1 \gamma_c A_c y_t}} \left[nA_{ps} f_{pi} \left(\frac{e_p y_t}{I_c} - \frac{1}{A_c} \right) - a_1 \sqrt{f_{ci,g}} \right]$$
(6)

$$l > \sqrt{\frac{I_c}{b_1 \gamma_c A_c y_b}} \left[nA_{ps} f_{pi} \left(\frac{e_p y_b}{I_c} + \frac{1}{A_c} \right) - a_2 f_{ci,g}^{'} \right]$$

$$(7)$$

$$l < \sqrt{\frac{nA_{ps}f_{pe}\left(\frac{e_{p}y_{t}}{I_{c}} - \frac{1}{A_{c}}\right) + a_{4}f_{c,g}^{'}}{\left[\frac{b_{1}\gamma_{c}A_{c} + b_{2}\left(\gamma_{c,d}A_{d} + w_{c}\right)\right]y_{t}}{I} + \frac{b_{3}w_{l}y_{t,g}^{*}}{I^{*}}}}$$
(8)

$$l < \sqrt{\frac{\frac{nA_{ps}f_{pe}\left(\frac{e_{p}y_{b}}{I_{c}} + \frac{1}{A_{c}}\right) + a_{3}\sqrt{f_{c,g}}}{\left[\frac{b_{1}\gamma_{c}A_{c} + b_{2}\left(\gamma_{c,d}A_{d} + w_{c}\right)\right]y_{b}}{I_{c}} + \frac{b_{3}w_{l}y_{b}^{*}}{I_{c}^{*}}}}$$
(9)

Plotting these four equations along the horizontal axis n and the vertical axis l, the domain of inequality can be formed, indicating a feasible design domain in which a possible range of span and the number of sheaths can directly be found. The dominant equations that are crucial in determining the possible maximum span can also be found. Another notable advantage of the proposed procedure is that the single or combined effect of changing the values of influencing factors on the span extension can be visualized by the change in shape of the design domain. Therefore, in a preliminary design of a long-span PSC girder bridge, the proposed procedure may be useful for a designer to choose strategies for the span extension and to determine an appropriate margin for stress limit. The strategies can be reflected in the variables included in the graphs, as shown in Table 1.

3.3 Other cases

Options for span extension	Relevant variables	
High strength concrete	$f_{ci,g}^{'}$, $f_{c,g}^{'}$, and $f_{ci,d}^{'}$	
Lightweight concrete	γ_c and $\gamma_{c,d}$	
Increased diameter of strand	A_{ps}	
High strength strand	$f_{_{pi}}$ and $f_{_{pe}}$	
Optimization of section shape	$I_{c}, A_{c}, I_{c}^{*}, A_{c}^{*}, y_{t}, y_{b}, y_{t,g}^{*}, y_{t,d}^{*}, y_{b}^{*}, e_{p,1}^{*}, e_{p,2}^{*}, \text{ and } e_{p,2}^{*}$	
Girders made continuous	b_2 and b_3	
Increased allowable stresses	a_1 , a_2 , a_3 , and a_4	
More accurate (reduced) live load distribution factor	w _l	

Table 1 Strategies for span extension and corresponding variables

Typical multistage prestressing consists of two stages. First, prestress of the first group of tendons is introduced to a girder. After the girders are erected in place onto piers or abutments and the deck is placed, the second group of tendons is posttensioned. If the secondary prestressing is performed before the deck is hardened sufficiently to develop composite action with the girder, the relevant eight equations can be derived as proposed by Jeon et al. (2012). On the other hand, if the secondary prestressing is performed after the deck is hardened, some of the equations are slightly modified as presented by Jeon et al. (2012).

For the decked PSC girder system as shown in Fig. 1, the top fiber stress of the deck and the bottom fiber stress of the girder are verified at the time of prestressing and in service. Eqs. (6) and (7) are similarly adopted, with an additional consideration of the self-weight of the deck and cross beams and of composite action. Eqs. (8) and (9) are also used with a slight modification considering the composite action.

4. EXAMPLES OF SPAN EXTENSION OF PSC GIRDER BRIDGE

4.1 General remarks

In the preceding section, the primary concept of the proposed graphical approach to assess the possible span range of a PSC girder bridge was stated. To verify the procedure and to demonstrate a number of advantages expected, a sample PSC girder bridge with five girders is analyzed, as shown in Fig. 2. The span extension, which is achievable by applying one or a combination of the aforementioned strategies, is examined with the section dimensions unchanged for a fair comparison, except when the section optimization is considered. The AASHTO specifications (2010) are referred to for basic design criteria. The effective flange width that accounts for contribution of the deck to a resistance of the composite section is 2.5 m for the interior girder, which will be analyzed. Design vehicular live load is highway loading-93 (HL-93). Each sheath

contains 12 12.7-mm strands ($A_{ps} = 12 \times 98.71 \times 10^{-6} = 1.1845 \times 10^{-3}$ m²). The specified tensile strength of the strand f_{pu} is 1,860 MPa, and f_{pi} and f_{pe} are 1,150 and 980 MPa, respectively. According to the typical practice in Korea, $f_{ck,g}$ and $f_{ci,g}$ are



Fig. 2 Sample prestressed concrete girder bridge

40 and 32 MPa, respectively, and $f_{ck,d}$ and $f_{ci,d}$ are 27 and 21.6 MPa, respectively. Cross beams with a thickness of 0.3 m are located at supports, quarter points, and middle of the span.

To evaluate the effect of live load or secondary dead load on each girder, a number of finite element analyses were performed for the entire bridge with various types of live load configurations using ABAQUS (Dassault Systèmes Simulia Corporation 2009). The resulting equivalent distributed live load w_i and equivalent distributed load of cross beams w_c did not exceed 20 and 2 kN/m, respectively. Therefore, these two values are consistently used during the analysis from a conservative point of view. The coefficients regarding allowable stresses are $a_1 = 0.25$ (with $f_{ci,g,ta} < 1.4$ MPa), $a_2 = 0.60$, $a_3 = 0.50$, and $a_4 = 0.60$ (for all load combinations).

4.2 Span extension in each strategy

4.2.1 Standard PSC girder

The standard section of the PSC girder with a portion of the deck attached within the effective flange width is shown in Fig. 2. The parameters used in the analysis are $\gamma_c = \gamma_{c,d} = 24,517 \text{ N/m}^3$; $A_c = 0.8067 \text{ m}^2$; $A_d = 0.625 \text{ m}^2$; $I_c = 0.4795 \text{ m}^4$; $A_c^* = 1.3697 \text{ m}^2$; $I_c^* = 1.0153 \text{ m}^4$; $y_t = 1.143 \text{ m}$; $y_b = 1.057 \text{ m}$; $y_{t,g}^* = 0.622 \text{ m}$; $y_{t,d}^* = 0.872 \text{ m}$; $y_b^* = 1.578 \text{ m}$; $e_p = 0.929 \text{ m}$; and $b_1 = b_2 = b_3 = 0.125$. The modular ratio of the girder and deck is taken into account when calculating the preceding cross-sectional properties.

The result of applying the proposed procedure is shown in Fig. 3. The standard

girder with five sheaths shown in Fig. 2 has been used in Korea for highway bridges with a 35-m span when designed to the Korea Highway Bridge Design Code (Korea Road and Transportation Association 2005). Fig. 3 shows that the 35-m span is still within a feasible design domain even when designed to AASHTO specifications (2010). Although a total of four or five sheaths are possible to achieve the 35-m span, the latter provides more margin for stress limit. A higher margin for stress limit can be ensured as







Fig. 4 Span assessment of high-strength prestressed concrete girder

the target point moves inward from a boundary of the feasible design domain. Fig. 3 also shows that the span can reach 39 m with five sheaths. Most importantly, Fig. 3 implies that the girder can be used to cover a span of up to 43 m by arranging as many as six sheaths. Another notable feature of the procedure is that some important equations that have a significant effect on the possible maximum span can be easily distinguished. The corresponding equations in Fig. 3, for example, are those indicating the bottom fiber stresses at prestressing and in service. In this way, a significant amount of useful information can be obtained from the proposed graphical assessment.

4.2.2 Effect of high-strength concrete

The effect of concrete strength on the span is investigated by comparing the original strength (40 MPa) of the girder with the increased strengths (60 and 80 MPa),

with the strength of the deck maintained as 27 MPa. Certainly, the strength increase contributes to the span extension by increasing the allowable stresses of concrete. Feasible design domains corresponding to each strength are shown in Fig. 4, in which, for brevity, the four graphs that form each feasible design domain are not shown. The original span of 43 m can be considerably extended up to 54 and 61 m for concrete strengths of 60 and 80 MPa, respectively. By examining Figs. 3 and 4 it can be seen that this can be primarily attributed to the translation of the graph of the bottom fiber stress at prestressing as the strength increases.



Number of sheaths

Fig. 5 Span assessment of prestressed concrete girder with optimized section

4.2.3 Effect of lightweight concrete

The two cases in which the lightweight concrete is applied to the deck or to both the deck and girder are analyzed in an attempt to investigate the effect of reduced self-weight on the span extension. The unit weight of the lightweight concrete is taken as 18,829 N/m³ for the deck and 19,613 N/m³ for the girder in reference to the current practice (Liles and Holland 2010; Melby et al. 1996). It shows that the span can be extended up to 47 m by applying the lightweight concrete to the deck or to both the deck and the girder. The former case requires one additional sheath, whereas the latter case can maintain the same number of sheaths when compared with the standard PSC girder.

4.2.4 Effect of section optimization

Analysis is carried out on how the increase in the flexural efficiency of a section affects the span extension. When choosing an optimized section, some of the previous studies (Bardow et al. 1997; Meir et al. 1997) were referred to in terms of section shape. The coefficient of section efficiency given in Eq. (1) is adopted as the primary index to evaluate the flexural efficiency. For a fair comparison, the area (i.e., the amount of concrete) is maintained during the analysis. The coefficients of the original section shown in Fig. 2 are 0.492 and 0.539 before and after composite action with a deck, respectively, whereas those of the Bulb-Tee section with an increased upper flange width and a decreased web thickness, as shown in Fig. 5, derived through an

optimization are increased to 0.555 and 0.562, respectively. As a result of improving the section details, the span can be increased by 4 m compared with the original section as shown in Fig. 5.

4.2.5 Effect of continuity of girders

An example is taken whereby two girders occupying two equal spans are made continuous. If the continuity is made when a deck is placed (case 1 in Fig. 6), the moment coefficient b_3 introduced previously is reduced to 0.07 (56% of 0.125 for a simple span). On the other hand, both b_2 and b_3 can be reduced to 0.07 if the girders are made continuous before the deck placement (case 2 in Fig. 6). The spans extended by the continuity are 49 m (case 1) and 57 m (case 2).



Fig. 6 Span assessment of prestressed concrete girder made continuous









Fig. 8 Span assessment of decked prestressed concrete girder

4.2.6 PSC girder using multistage prestressing

The basic information of the girder using multistage prestressing is taken to be the same as that of the standard PSC girder. The eccentricities of primary and secondary prestressing tendons are $e_{p,1} = 0.929$ m and $e_{p,2} = 0.857$ m, respectively. One of the advantages of the proposed graphical procedure is that the span extension owing to any strategy can be logically explained. In case of the secondary prestressing before composite action of deck, Fig. 7(a) shows the feasible design domain that is formed by eight equations when assuming one sheath for secondary prestressing. The details of the derivation can be found in the study by Jeon et al. (2012). By comparing Fig. 7(a) with Fig. 3, it can be observed that the span is extended by the multistage prestressing in such a way that the two graphs corresponding to the stresses in service move upward. In this way, a greater number of sheaths can be arranged by the multistage prestressing, resulting in span extension, compared with the single-staged standard PSC girder. As the number of secondary sheaths increases, the graphs corresponding to the stresses at secondary prestressing also move upward. The

possible maximum number of secondary sheaths can be obtained by examining when the feasible design domain no longer exists because these two graphs have moved upward. In this example, it was found that as many as five secondary sheaths can be arranged, although only the cases of two and four secondary sheaths are shown in Fig. 7(b), with the extended spans of 51 and 53 m, respectively. The span is not extended longer than 53 m even for five secondary sheaths. On the other hand, the case of the secondary prestressing after composite action of deck can also be taken into account with some modification of the equations.

4.2.7 Decked PSC girder

The concrete strength of the deck part of the decked PSC girder is assumed to be 40 MPa, which is the same as that of the girder because the deck and girder are placed together. The parameters used in the analysis of the decked girder are: $A_c^* = 1.4317$ m²; $I_c^* = 1.0487 \text{ m}^4$; $y_{t,d}^* = 0.839 \text{ m}$; $y_b^* = 1.611 \text{ m}$; and $e_p^* = 1.438 \text{ m}$. Fig. 8 shows that the area of the feasible design domain of the decked girder is considerably enlarged, resulting in a span extension of up to 61 m.



Fig. 9 Comparison of extended span lengths

4.3 Summary of analysis results

The analysis results are shown in Fig. 9 and Table 2. The results can be used to create a prioritized list of alternatives that contribute to extending the span range. In this example, the application of high-strength concrete, the deck-integrated fabrication of PSC girder (decked PSC girder), PSC girders made continuous, and multistage prestressing have a significant effect on the span extension. The results show a similar trend to another prioritized list made by conventional design procedure (Castrodale and

White 2004).

It is estimated that the span of the girder with a 2.2-m height that has been originally used in Korea for highway bridges with a 35-m span can be extended up to 50-60 m by applying any particular strategy when designed to the AASHTO specification (2010). If it is to be further extended up to 70 m, however, a combination of the strategies may be more preferable to the single strategy, along with a reasonably increased girder height, if necessary.

5. CONCLUSIONS

Conventional PSC girder bridges have been primarily used for short to medium spans less than 40 m. Longer-span girders, however, with 50- to 70-m span or more, which usually belongs to a span range of box girder bridges, are becoming increasingly more popular. In this respect, a number of strategies have been proposed to extend the span of PSC girder bridges, because simply increasing a girder height is not sufficient to maximize economic efficiency, constructability, and aesthetics. This paper presents a systematic procedure that can be used to assess the contribution of these strategies to the span extension. The proposed scheme adopts a graphical approach that represents a relationship between the number of prestressing tendons and the span

Strategy for a longer span		Remarks	Maximum number of sheaths ⁽²⁾	Maximum span (% increase)	Ranks in span
None	Standard PSC girder ⁽¹⁾	Refer to Fig. 2 (Girder height: 2.2 m)	6	43 m	10
Material- related	High strength concrete I	$f_c^{'}$ of girder: 40 MPa \rightarrow 60 MPa	10	54 m (+26%)	4
	High strength concrete II	f_c of girder: 40 MPa \rightarrow 80 MPa	13	61 m (+42%)	1
	Lightweight concrete I	Unit weight of deck: 24,517 N/m ³ → 18,829 N/m ³	7	47 m (+9%)	8
	Lightweight concrete II	"Lightweight concrete I" + Unit weight of girder: 24,517 N/m ³ → 19,613 N/m ³	6	47 m (+9%)	8
Design- and construction -related	Section optimization	I shape → Bulb Tee shape (Same height and area)	7	47 m (+9%)	8
	Continuity I	Two spans	7	49 m	7

Table 2 Summary of analysis results of span

		continuous for live load and secondary dead load		(+14%)	
	Continuity II	"Continuity I" + Two spans continuous for self- weight of deck and cross beams	8	57 m (+33%)	3
	Multistage prestressing I	Secondary prestressing before composite action of deck	7 (primary) + 5 (secondary)	53 m (+23%)	5
	Multistage prestressing II	Secondary prestressing after composite action of deck	7 (primary) + 2 (secondary)	50 m (+16%)	6
	Decked PSC girder	Fabrication of deck- integrated girder	11	61 m (+42%)	1

Note:

(1) This girder has actually been used in Korea for 35 m span with five sheaths.

(2) The maximum number of sheaths and anchorages also depends on the section shape. If the number is too great to arrange within a given section, the number can be reduced by using larger-sized or an increased number of strands within a larger-sized sheath or by using high strength strands.

and is derived on the basis of stress assessment equations of the girder at each stage of fabrication and in service. Through manipulation of the equations, the feasible design domain can be formed, which can accommodate a designer's decision to choose some appropriate strategies to achieve the required span. The possible maximum span and the corresponding number of tendons can be readily determined from the feasible design domain without the trial-and-error-based conventional design procedure. Furthermore, depending on the target point a designer chooses within the domain, the margin for stress limit of the design can also be adjusted. By comparing the shapes of the domains, which vary according to the strategies applied, the designer can prioritize the strategies in terms of span extension without significant effort.

A quantitative evaluation for the span extension is performed by adopting a sample bridge to demonstrate a number of aforementioned advantages of the proposed scheme. The results imply that increasing the strength of the girder, the decked PSC girder, PSC girders made continuous before a deck placement, and multistage prestressing with the secondary tendons prestressed before composite action of the girder and deck are very effective and, therefore, would be essential components for extending the span.

REFERENCES

AASHTO (2002), Standard Specifications for Highway Bridges, 17th Ed., AASHTO, Washington, DC.

AASHTO (2010), AASHTO LRFD Bridge Design Specifications, 5th Ed., AASHTO,

Washington, DC.

- Abdel-Karim, A.M. and Tadros, M.K. (1992), *State-of-the-Art of Precast/Prestressed Concrete Spliced I-Girder Bridges*, Precast/Prestressed Concrete Institute (PCI), Chicago.
- ASTM (2006), Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete, A416/A416M-06, West Conshohocken, PA.
- Bardow, A.K., Seraderian, R.L. and Culmo, M.P. (1997), "Design, fabrication and construction of the New England Bulb-Tee girder", *PCI J.*, **42**(6), 30-40.
- Boczkaj, B.K. (1994), "Section fully utilized in prestressed concrete", *PCI J.*, **39**(6), 90-98.
- Castrodale, R.W. and White, C.D. (2004), *Extending Span Ranges of Precast Prestressed Concrete Girders*, National Cooperative Highway Research Program (NCHRP) Rep. 517, Transportation Research Board, Washington, DC.
- Cisneros, R.A., Fulginiti, L.H., Krause, S.L., Medlock, R.D. and Wandzilak, T.J. (2008), "Decked girders for accelerated bridge construction", *Proceedings of Accelerated Bridge Construction-Highway for Life Conference*, Federal Highway Administration (FHWA), Washington, DC, 157-162.
- Dassault Systèmes Simulia Corporation (2009), *ABAQUS 6.9-Analysis User's Manual*, Providence, RI.
- Guyon, Y. (1963), *Prestressed Concrete*, Wiley, New York.
- Han, M.Y., Hwang, E.S. and Lee, C.D. (2003), "Prestressed concrete girder with multistage prestressing concept", *ACI Struct. J.*, **100**(6), 723-731.
- Issa, M.A., Anderson, R., Domagalski, T., Asfour, S. and Islam, M.S. (2007), "Full-scale testing of prefabricated full-depth precast concrete bridge deck panel system", *ACI Struct. J.*, **104**(3), 324-332.
- Janssen, B.S. (2010), "Going to record lengths", ASPIRE, Winter, 24-27.
- Jeon, S.J., Choi, M.S. and Kim, Y.J. (2012), "Graphical assessment for span ranges of PSC girder bridges", *J. Bridge Eng.*, *ASCE*, **17**(2), 343-352.
- Korea Road and Transportation Association (KRTA) (2005), Korea Highway Bridge Design Code, Seoul, Korea.
- Lavallee, R. and Cadman, K. (2001), "New England Bulb Tee girder brings strength, elegance and economy to Jetport Interchange Bridge", *PCI J.*, **46**(6), 68-75.
- Liles, P. and Holland, R.B. (2010), "High strength lightweight concrete for use in precast, prestressed concrete bridge girders in Georgia", *HPC Bridge Views*, **61**, 1-3.
- Meir, J.V., Cicciarelli, M.R., Ramirez, J.A. and Lee, R.H. (1997), "Alternatives to the current AASHTO standard bridge sections", *PCI J.*, **42**(1), 56-66.
- Melby, K., Jordet, E.A. and Hansvold, C. (1996), "Long-span bridges in Norway constructed in high-strength LWA concrete", *Eng. Struct.*, **18**(11), 845-849.
- Naaman, A.E. (2004), *Prestressed Concrete Analysis and Design Fundamentals, 2nd Ed.*, Techno Press 3000, Ann Arbor, MI.
- Precast/Prestressed Concrete Institute (PCI) (2003), *Precast Prestressed Concrete Bridge Design Manual, 2nd Ed.*, Precast/Prestressed Concrete Institute, Chicago.
- Smith, M.Z., Li, Y. and Ahlborn, T.M. (2008), "Analysis of longitudinal joint connections for decked precast prestressed concrete girder bridges", *Proceedings of Accelerated Bridge Construction-Highway for Life Conference*, Federal Highway Administration (FHWA), Washington, DC, 121-126.