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 long-span 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.

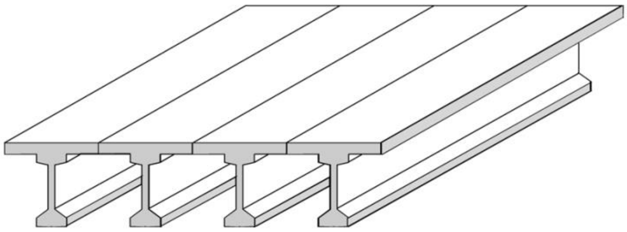

Fig. 1 Decked prestressed concrete girder bridge

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-and-error-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