파형강판 PSC 박스거더 교량의 설계 및 시공중 안전관리

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Design and Safety Control in Construction Stage of Prestressed Concrete Box Girder Bridge with Corrugated Steel Web

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Abstract : The Ilsun Bridge is the world's longest box girder bridge(801m) with corrugated steel webs and has the widest width(21.2~30.9m: tri-cellular cross section) among these kinds of composite girder bridges. It has fourteen spans(50m, 10 at 60m, 50m, 2 at 50.5m) where twelve spans are erected by the incremental launching method and two spans by full staging method. Special topics related to the structural safety of prestressed concrete box girder bridge with corrugated steel web in construction stage and service were reviewed. Investigations focus on the span-to-depth ratio, shear stress of corrugated steel webs and optimization of the length of steel launching nose. The span-to-depth ratio of Ilsun bridge has been found to be well-planned while the corrugated steel web has been designed highly conservative and it has been observed that the conventional nose-deck interaction equation do not fit well with corrugated steel web bridges. As a result, detailed construction stage analysis was performed to check the stress levels and the safety of preceding design conditions. Finally, from the design review of Ilsun bridge, this study suggests optimal design issues which should be of interest in designing a prestressed concrete box girder bridge with corrugated steel webs.

요 약 : 일선대교는 복부 파형강판 복합교량 형식으로서 연장과 폭원으로는 세계 최대의 규모이다. 총 14개 경간으로 구성된 일선대교는 압출공법(ILM)에 의하여 12개 경간이 연속구조로 건설되고 나머지 2개 경간은 동바리공법(FSM)에 의하여 건설된다. 본 논문에서는 동일한 구조형식으로는 국내에서 최초로 건설되며 해외에서도 유례가 없는 광폭과 장경간의 복부 파형강판 복합교량인 일선대교를 압출공법에 의하여 시공하면서 수행된 구조 안전성 분석과 관련된 주제들을 다루고 있다. 이러한 과정을 통하여 지간-형고비, 복부 파형강판의 전단응력, 그리고 압출 추진코의 최적 길이 등이 파형강판 복합구조 교량의 시공중 및 사용중 안전성에 큰 영향을 미칠 수 있는 것으로 분석되었다. 특히, 일선대교와 같은 복부 강재구조를 갖는 복합교량은 박스거더, 추진코, 그리고 연결 격벽의 강성 차가 크기 때문에 기존의 방법에 의한 단면력 분석은 적합하지 않은 것으로 확인되었다. 이에 따라 압출 추진코의 길이, 구조물의 강성 등을 변수로 압출중 최대 부모멘트에 대한 검토를 수행하였으며 최종적으로는 상세 구조해석을 통하여 구조물의 시공중 안전성을 확인하였다.

Key Words : prestressed concrete box girder bridge with corrugated steel web, incremental launching, span-to-depth ratio, design shear stress, nose-optimization, construction stage analysis

1. Introductions

The Ilsun Bridge is a composite bridge, 801m long whose superstructure is consisted of prestressed concrete slabs and corrugated steel webs. The bridge has fourteen spans as shown in Fig. 1 where twelve spans are erected by the incremental launching method while two spans near the east bank are constructed by full staging method.

The transverse cross-section shown in Fig. 2 erected by the incremental launching method is 21.2m wide and is widened to 30.9m at the east side of the river where full staging is applied. Four lanes of traffic

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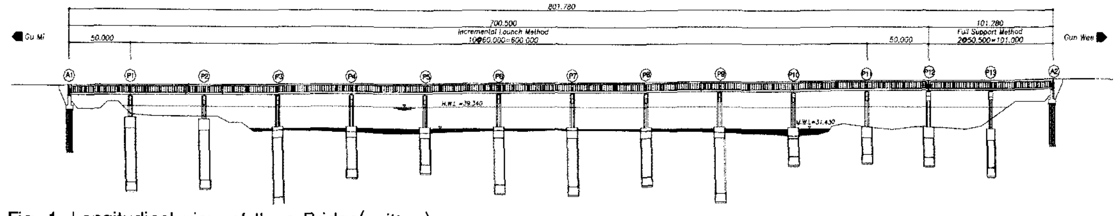

Fig. 1. Longitudinal view of Ilsun Bridge(unit: m).

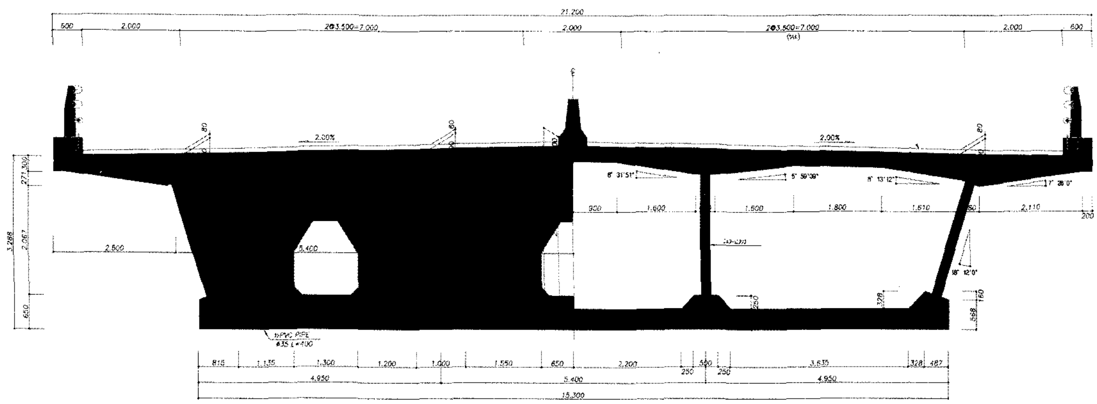

Fig. 2. Typical superstructure transverse cross-section(unit: m).

were required for Ilsun bridge to be compatible with the existing road network and it was hydraulically more lucrative to reduce the number of piers with one wide tri-cellular cross section than having a double number of piers supporting each single-cellular box girder for opposite traffic lanes. Transverse prestressing was also applied in the concrete slab in order to resist the traffic live load since the tri-cellular cross section was designed to be supported by the corrugated steel webs every 5.4m.

Four types of bridges, a steel box girder bridge with a concrete deck, a prestressed concrete box girder bridge, an extradosed bridge and a prestressed concrete box girder bridge with corrugated steel webs were selected as possible options during the first planning of this bridge. The alignment, hydraulic characteristics of the river, structural efficiency, economic thresholds, aesthetic standards and environmental conditions had been considered in discussions before choosing the final type. The alignment of the bridge was limited to 0.3% approach gradients with a 60% of upstream linear alignment(skewed 30 degrees to the flow direction) and the carriageway width was planned to be 21.2m, respectively to be compatible with the existing road network. The number of piers and the span length were determined from hydraulic analysis results in order to control the design flood water level under 39.34m for a flood discharge of 12,580m^3/sec within a 100year design frequency.

As a result, the total bridge length(801m) was divided into 10 spans of 60m, 2 spans of 50m and 2 spans of 50.5m with 13 piers(Fig. 1). Moreover, environmental conditions of the river having a water intake nearby prevented the use of temporary support structures usually submerged in the river during the construction, and so the deck had to be constructed using the incremental launch method, similar as the Serio River Bridge in Italy[1)]. The design span length of 60m in 10 spans decided from the hydraulic analysis results and the construction method selected by taking environmental conditions in consider, has limited the use of steel box girders for complex camber control during the launching process. In addition, the use of prestressed concrete box girders had been preferred to steel box girders because of the instability problems faced in designing steel structures. On the contrast, combining the use of concrete slab and steel web with external prestressing increases the radius of gyration by concentrating the mass at the edges and consequently permits savings in prestressing[2]. This is the main idea of bridges with corrugated steel webs first practiced in France and the advantages of prestressed concrete box girder bridges with corrugated steel webs have been confirmed by previous field practices and researches. Corrugated steel webs have low axial stiffness so that it could avoid the migration of prestressing toward the webs and also prevent the presence of internal stresses due to the deformation of concrete slabs. As a result, the thickness of web plate can be reduced and design can focus on strength criteria instead of stability problems. In addition, there is no need for additional stiffeners due to the sufficient transverse flexural stiffness which prevents buckling and makes corrugated steel web competitive compared with the cost of folding. For such reasons, the use of corrugated steel web has been highly considered.

2. Design review of Ilsun Bridge

2.1. Span-to-depth ratio

The span-to-depth ratio is important in designing the bridge superstructure since providing a maximum clearance with minimum approach grades is common requirement for a designer. The AASHTO LRFD Bridge Design Specifications[3] specifies overall cross-section dimensional ranges to provide satisfactory deflection limit of $l/1000$ for segmental concrete bridges. They recommend the maximum span-to-depth ratio as 30:1 and 50:1 for constant depth girders and variable depth girders with circular or parabolic haunches, respectively. In addition, for incrementally launched girders they preferably recommend maximum span-to-depth ratio near 12:1.

The AASHTO LRFD design line and the span-to-depth ratio of prestressed concrete box girder bridges with corrugated steel webs built up to date are shown in Fig. 3. According to the data compared with the design line for segmental concrete bridges, most of the bridges with corrugated steel webs have similar cross-section with the concrete box girder bridges except for the Yahagigawa bridge, Himi bridge and the Ouchiyamagawa second bridge which exceeds the maximum span-to-depth ratio. The Ouchiyamagawa second bridge is the most recent work(constructed in 2002) of corrugated steel web bridges using only external prestressing with no internal tendons in the concrete slab. By the support of applying merely ex-

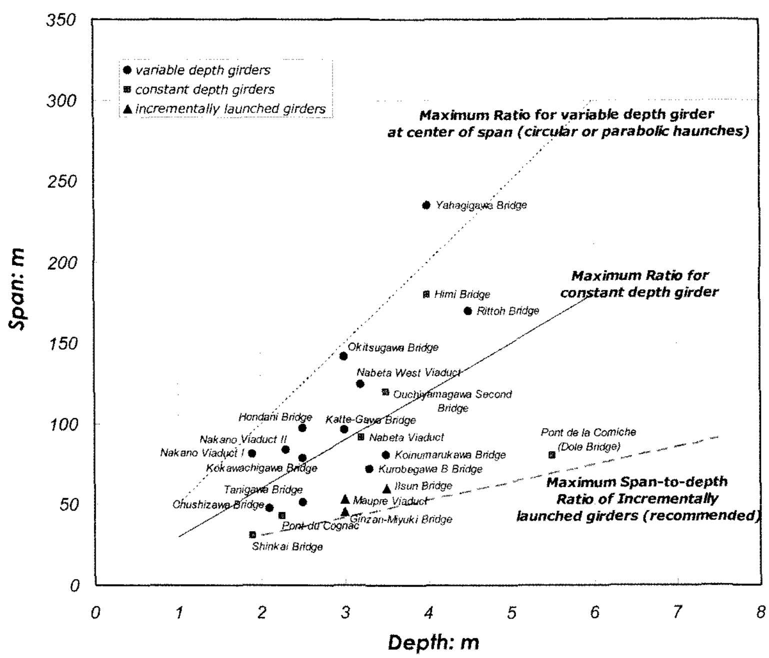

Fig. 3. Span-to-depth Ratio of Prestressed Concrete Bridges with Corrugated Steel Webs.

ternal tendons, the project has dictated high span/depth ratio near 34. However, the Yahagigawa bridge and the Himi bridge are not only composite bridges with corrugated steel webs but also cable-supported bridges: a cable-stayed bridge and an extradosed bridge, which may be the reason they have extraordinary span/depth ratios much higher than ordinary corrugated steel web bridges. In contrast to others, Pont du Cognac(Cognac bridge) and Pont de Corniche (Dole bridge) of France and the Shinkai bridge of Japan have low span/depth ratio with a deeper section, yet these three are the early tryouts of using corrugated steel webs. Although, the corrugated steel web bridges constructed by cantilevering or segmental precasting have similar span/depth ratio with segmental concrete box girder bridges, bridges constructed by incremental launching showed that utilizing corrugated steel webs can increase the span-to-depth ratio higher than the recommended design line of concrete box girder bridges. The Ilsun bridge designed to be constructed by incremental launching showed the highest span/depth ratio near 17 among the similar cases. The value is higher than normal segmental concrete box girder bridges which are incrementally launched.

2.2. Shear stress of the corrugated steel web

According to Sayed-Ahmed[4], there are two ways of design methods in determining the dimension of the corrugated steel web and these two methods can be distinguished from the different process in calculating the critical interactive buckling stress. Previous researches suggests the critical interaction buckling stress $\tau_{cr,i}$ as the following equation,

$$\frac{1}{(\tau_{cr,i})^n}=\frac{1}{(\tau_{cr,l})^n}+\frac{1}{(\tau_{cr,g})^n} \tag{1}$$

where $\tau_{cr,l}$ and $\tau_{cr,g}$ are the critical local buckling stress and the critical global buckling stress, respectively.

Bergfelt and Leiva-Aravena[5] proposed $n = 1$ based on experimental analysis while Lindner and Aschinger[6] suggested $n=2$ which is derived from an elastic interaction buckling formula. El-Metwally and Loov[7] proposed a different interaction equation including the yielding failure mode to the local and global buckling modes.

$$\frac{1}{(\tau_{cr,i})^n}=\frac{1}{(\tau_{cr,l})^n}+\frac{1}{(\tau_{cr,g})^n}+\frac{1}{(\tau_y)^n} \tag{2}$$

where τ_y is the shear yield stress of corrugated steel web.

As Sayed-Ahmed[4] summarized, the two ways of design methods in determining the dimension of the corrugated steel web can be distinguished from choosing whether Eq. (1) or Eq. (2). The first method[8] which was practiced in France choose the design shear stress of corrugated steel web τ_d from taking the minimum value of interactive design buckling stress τ_{id}, global design buckling stress τ_{gd} and the local design buckling stress as τ_{ld}:

$$\tau_d=\min(\tau_{id},\ \tau_{gd},\ \tau_{ld}) \tag{3}$$

The interactive buckling design stress τ_{id} and the global buckling design stress τ_{gd} are obtained by multiplying a design value k_i and k_g respectively, which considers the imperfection and residual stresses of the steel web to the critical interactive buckling stress $\tau_{cr,i}$ and critical global buckling stress $\tau_{cr,g}$.

$$\tau_{id}=k_i\cdot\tau_{cr,i} \tag{4}$$

$$\tau_{gd}=k_g\cdot\tau_{cr,g} \tag{5}$$

Here, the critical interactive buckling stress $\tau_{cr,i}$ is calculated using Eq. (1). The global buckling stress $\tau_{cr,g}$ characterized by diagonal buckling over several corrugation panels can be defined by the following equation[9].

$$\tau_{cr,g}=36\beta\frac{D_x^{1/4}D_z^{3/4}}{h_w^2t_w} \tag{6}$$

where h_w is the depth of web and t_w is the thickness of web.

The value of β varies from 1 to 1.9[10] and in design practice $\beta=1$ is used for simply supported edges while $\beta = 1.9$ is used for clamped edges. Johnson and Cafolla[8] suggested $\beta = 1.678$ for case of composite girders with corrugated steel webs and concrete slabs. The relevant parameters of Eq. (6) are:

$$D_x = \left(\frac{c}{s}\right)\left(\frac{Et_w^3}{12}\right) = \left(\frac{b+d}{b+d\sec\alpha}\right)\left(\frac{Et_w^3}{12}\right) \tag{7}$$

$$D_z = \frac{EI_z}{c} = \frac{E}{b+d}\left(\frac{bt_w(d\tan\alpha)^2}{4} + \frac{t_w(d\tan\alpha)^3}{12\sin\alpha}\right) \tag{8}$$

where c is the wave length of the web. b, d and α is the width, depth and corrugated angle of the web, respectively. I_z is the second moment of area of one wave length of the web.

The local design buckling stress τ_{ld} can be expressed as the following equation considering the studies of the effects of geometrical imperfections and residual stresses.

$$\tau_{ld} = \frac{0.9\sqrt{\tau_{cr,l} \cdot \tau_y}}{\gamma_m} \tag{9}$$

Here, the critical local buckling stress $\tau_{cr,l}$ and the shear yield stress τ_y can be derived from the classical elastic critical analysis and von Mises yield criterion, respectively as the following:

$$\tau_{cr,l} = k_s \frac{\pi^2 E}{12(1-\upsilon^2)}\left(\frac{t_w}{b}\right)^2 \tag{10}$$

$$\tau_y = \frac{f_y}{\sqrt{3}} \tag{11}$$

The buckling coefficient k_s can be given by:

$$k_s = 5.34 + 2.31\frac{b}{h_w} - 3.44\left(\frac{b}{h_w}\right)^2 + 8.39\left(\frac{b}{h_w}\right)^3 \tag{12}$$

Eq. (12) is used when the long edges of the sub panels are simply supported while the short edges are clamped like most of the composite girders with corrugated steel webs. The design factor γ_m is 1.1 for buckling failures. Finally, by using the Eq. (1) through Eq. (12) the minimum design shear stress with various factors of safety can provide optimum proportions of corrugated steel web as shown in Fig. 4. According to Fig. 4, the web dimension of Ilsun Bridge can be improved remarkably up to 59% or 44% of the optimum value when the design stress is

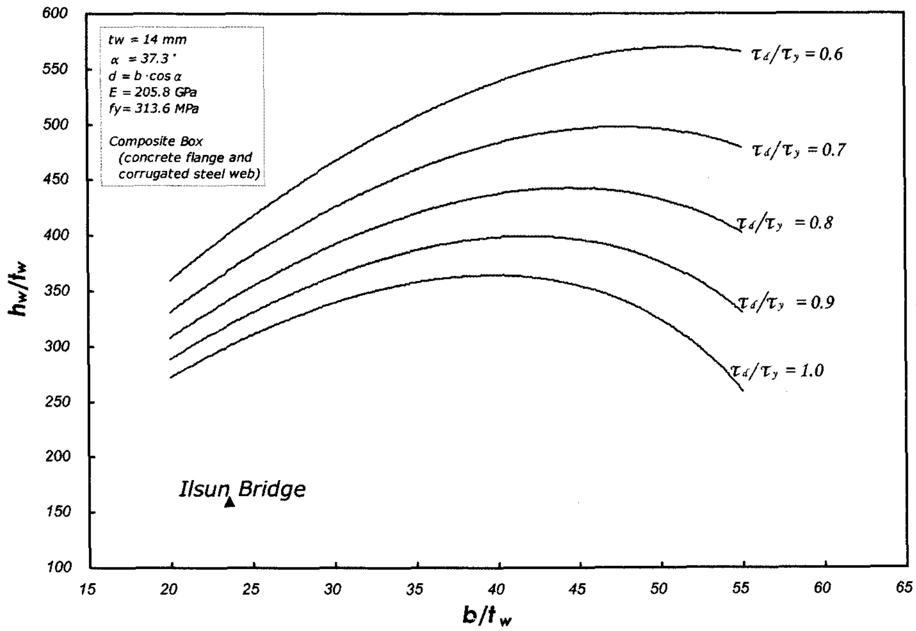

Fig. 4. Optimum proportions of corrugated steel web used in Ilsun Bridge.

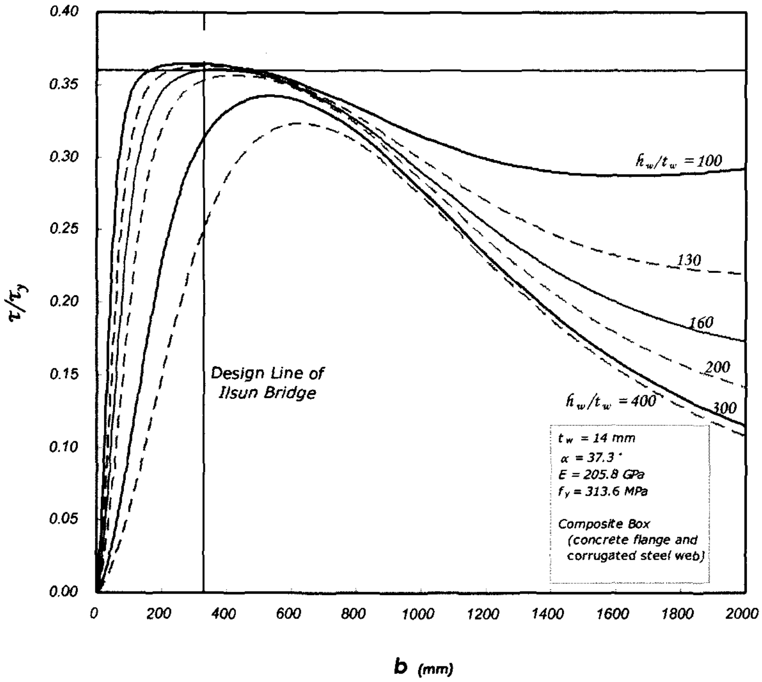

Fig. 5. Design chart of the corrugated steel web of Ilsun Bridge.

equal to the yield stress or 60% of the yield stress, respectively.

The other design method El-Metwally and Loov[7] has suggestes includes the yielding failure mode with global, local and interactive buckling mode. This method applies strength reduction factor at the final stage after plotting the design chart. Each web panels of Ilsun bridge has the same width b_w = 330 mm, since web panels are usually designed to have an identical width(d/b = cosα) in order to give same slenderness. The angle of corrugation α in Ilsun bridge is 37.3° a normal value for corrugated steel web panels which have a slope between 30° to 50°. The web thickness of Ilsun bridge varies from 14 mm(center span) to 20mm(pier) while the height varies from 2,241m(center span) to 2,292m(pier). A design chart of corrugated steel web for Ilsun Bridge is plotted on Fig. 5. The figure also shows that a conservative strength reduction factor ϕ = 0.36 was applied in design. Figs. 4 and 5 showed that the two different design methods have similar results. Though the Ilsun bridge has high span-to-depth ratio as an incremental launched bridge, the corrugated steel webs were shown to be designed highly conservative.

2.3. Stress control of box girder during launching process

To control the stresses in the front-zone during the launching process, it is common practice to apply the launching nose. Here, the behavior of the nose-deck elastic system is governed by the relative nose length l_n / l, the relative unit weight q_n / q and the relative flexural stiffness E_nI_n / EI[11]. According to Rosignoli[11], the behavior of nose-deck system is governed by the length and weight of the steel nose where the nose reaches the next pier while after reaching the next pier the stiffness of the nose governs the nose-deck interaction behavior. The theoretical model of nose optimization has been explicated by Rosignoli[12] and has been reviewed by Ahn, Yang and Lee[13]. The launching process starts from $x = 0$ until the nose contacts the next pier where $x = 1$. The distance of the deck from the support caused by the progression of launch varies through $x = l - l_n$ and the dimensionless launching progress α can be defined as Eq. (13). At the start of launch, the bending moment caused by the cantilever nose can be expressed as Eq. (14). This increases to an absolute value calculated by Eq. (15) as the launching progress starts.

$$\alpha = \frac{x}{l} \tag{13}$$

$$\frac{M}{ql^2} = -\frac{q_n}{2q}\left(\frac{l_n}{l}\right)^2 \tag{14}$$

$$\frac{M}{ql^2} = -\frac{\alpha^2}{2} - \frac{q_n}{q}\frac{l_n}{l}\left(\alpha + \frac{l_n}{2l}\right) \tag{15}$$

where M is the bending moment at the cantilever configuration. x is the launching progression distance of the front deck(the section with the nose attached). q_n is the unit weight of the launching nose and q is the unit weight of the front deck. l_n and l is the length of the nose and the length of the span, respectively.

From the review, the assumption that the nose and the deck are of constant stiffness and constant weight used in deriving Eq. (14) does not match for Ilsun Bridge. As shown in Figs. 6 and 7, the weight and stiffness of Ilsun Bridge are not constant in the longitudinal direction since the bridge is light in ordinary sections with corrugated steel web and relatively heavy in sections with a diaphragm.

Applying the mean stiffness in a two-dimensional frame model(longitudinal direction) shows that Rosignoli equation fits well with the FEM analysis results. However, as shown in Fig. 8 applying the actual stiffness to the frame model shows that the negative

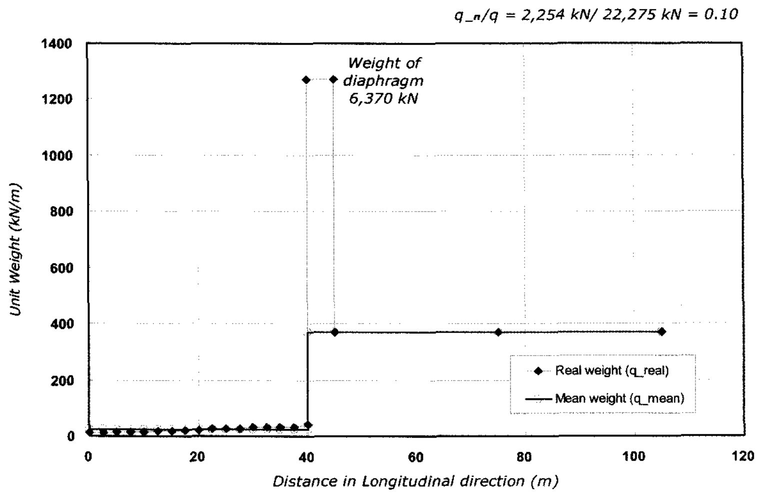

Fig. 6. Unit weight variation in longitudinal direction.

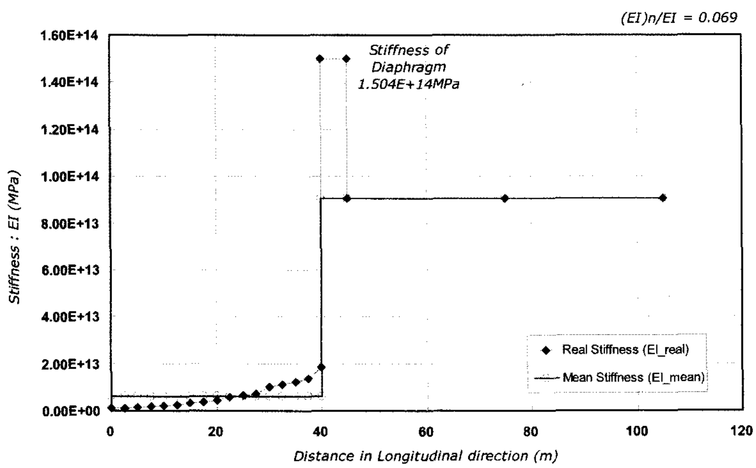

Fig. 7. Stiffness variation in longitudinal direction.

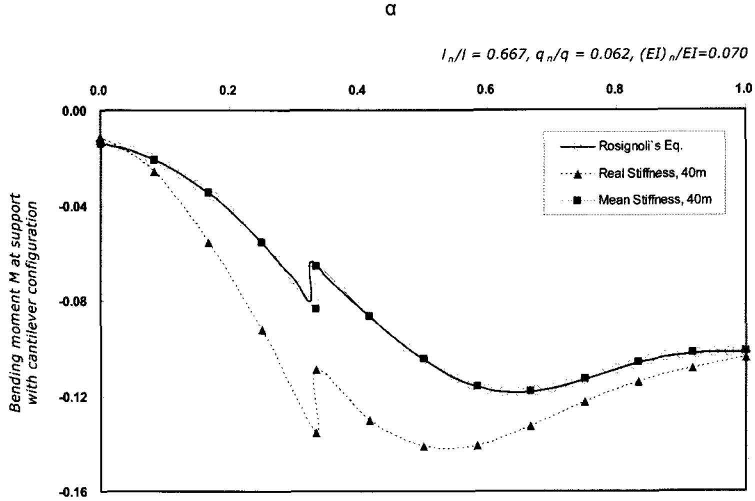

Fig. 8. Progression of moment at the support(Actual Stiffness v.s. Mean Stiffness).

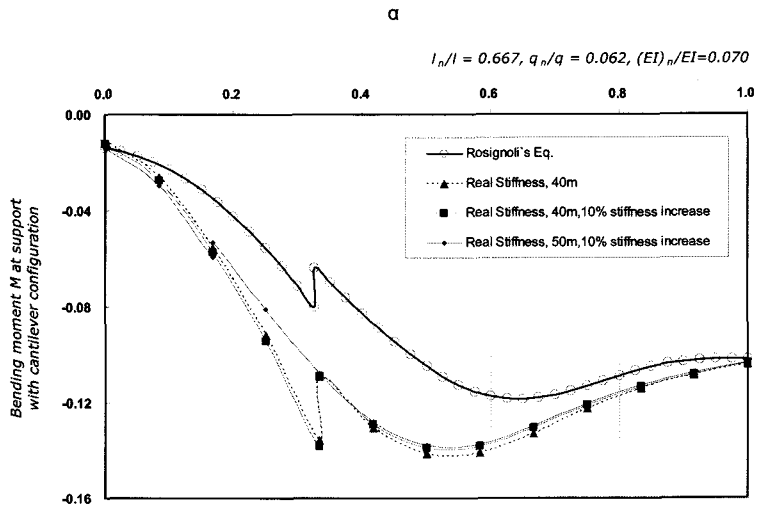

Fig. 9. Progression of Moment at the support(variation in nose length and stiffness).

bending moment at the support with cantilever configuration can be maximum 19.5% larger than the case with mean stiffness values as the assumption of Rosignoli equation. Fig. 9 shows that applying ten more percent of stiffness in frame analysis would not change the value of negative moment but increasing the nose length from 40m to 50m may decrease the negative bending moment. This explains that in applying incremental launching as a construction method for prestressed concrete box girder bridges with corrugated steel webs which have great difference in stiffness and weight throughout the longitudinal direction, it is efficient to design a longer launching nose so that the nose can reach the next pier earlier enough to decrease the negative moment.

Figs. 8 and 9 show that there are limitations in using the Rosignoli equation in optimizing the length of steel launching nose for composite bridges such as Ilsun bridge. Since the difference in weight and stiffness between the ordinary sections and the sections with diaphragms are much larger than the difference shown in conventional concrete box girder bridges[14]. Therefore, construction stage analysis with a detailed FEM model has been performed to check the safety and stress level of the superstructure with a 40m launching nose.

3. Safety control in construction stage

The most significant aspect of bridges built by the incremental launched method are that the cross section has to withstand the transitory stresses due to the maximum positive, negative moments and the maximum shear which occur on each section during the launching procedure. Since such transient stresses can influence the quality of construction, the structural behavior and stress distribution have been analyzed for each construction stage by nonlinear three-dimensional finite element analysis using the computer program DIANA. In the analysis, 8-node solid element HX24L was used to model the concrete slab and 4-node shell element Q20SF was used to model the corrugated steel web. The prestressing tendons were modeled by using the bar element and longitudinal axial force was applied on the bar element for each construction step[15].

Fig. 10 shows the launching process of Ilsun Bridge until the steel nose reaches the 3rd pier. The first segment is 5m in which the steel launching nose is attached while other segments are divided into 30m where the span length is 60m. During the entire launch process the largest negative moment take place when the nose just passes the third pier where the 7th segment is launched. In this 7th construction stage(where the 7th segment is launched), the tensile stress on the top surface of the upper concrete slab in 2nd segment just above the 2nd pier becomes the maximum value. Therefore, the critical check point of the construction stage analysis was the construction stage of 7th segment.

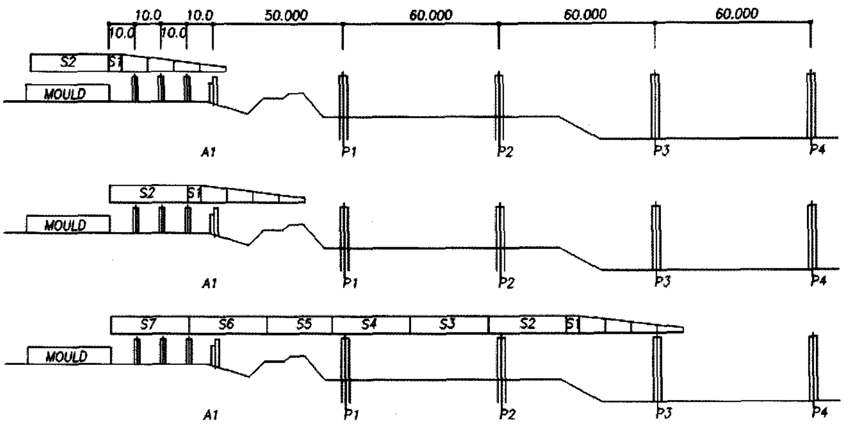

Fig. 10. Segmental launching process of Ilsun Bridge(7th construction stage).

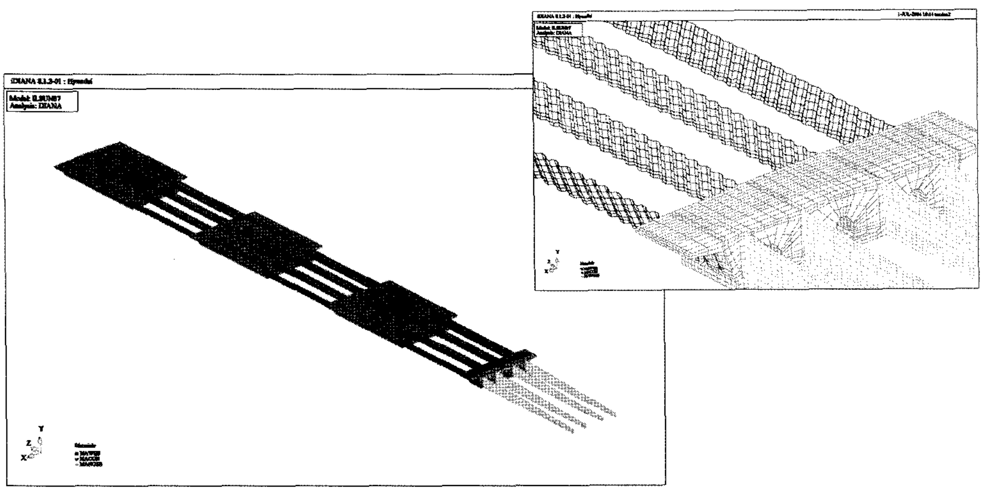

Fig. 11. Three-dimensional modeling of the 7th construction stage.

Fig. 11 presents the three-dimensional model of Ilsun bridge under the construction stage of 7^{th} segment. The finite element analysis results showed that the maximum tensile stress at this step is between 1.47 to 1.67MPa which is not a large value to induce crack. Although it would have been better if a longer steel launching nose was designed according to the Rosignoli equation, through detailed construction stage analysis it has been verified that the designed steel launching nose do not cause a harmful stress level during the launching. However, during the launching of 7th segment, the quality of the superstructure was closely controlled.

4. Conclusions

The Ilsun bridge is the first prestressed concrete girder bridge with corrugated steel web constructed in Korea, the widest and longest girder bridge with corrugated steel web in the world and the most efficient bridge application to have the maximum span-to-depth ratio through out incrementally launched composite bridges. As a general contractor in constructing such kind of bridge, special issues related to the design was reviewed during the construction. The span-to-depth ratio of bridges with corrugated steel web, the shear stress applied in designing the dimension of corrugated steel web and the optimized length of steel launching nose has been checked.

Through the design check, it has been found that prestressed concrete bridges with corrugated steel web constructed by the incremental launching can have higher span/depth ratio than usual prestressed concrete box girder bridges. As a result, the Ilsun bridge showed a high span/depth ratio of 17. However, the corrugated shear web has been designed highly conservative which is suggested to be improved in other cases of such application by using the design method suggested by El-Metwally and Loov[7] and cross checking the optimal web dimension explicated by Johnson and Cafolla[8].

The conventional nose-deck interaction equation suggested by Rosignoli[12] usually applied in designing the length of steel launching nose did not show satisfactory agreement with the calculated results of frame analysis. It has been found that corrugated steel web composite bridges have great weight and stiffness difference in the longitudinal direction of the superstructure since, the weight of ordinary sections with corrugated steel web is relatively light compared to sections with a diaphragm. Therefore, to check the safety and stress levels of the preceding design conditions detailed construction stage analysis was perfomed using the finite element method. The largest negative moment through the entire launching process was found to take place when the nose just passes the third pier where the 7^{th} segment is launched. As a result, the quality of the construction was accurately controlled during the actual construction procedure. No serious crack or problem occurred during the critical launching stage and the bridge has safely finished the final launching. However, to minimize the negative bending moment which occurs in the cantilever configuration during the launching it is recommended to maximize the length of nose using the conventional equation and control the construction safety of the superstructure through detailed construction stage analysis and field measurements.

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