The high-performance steels of HSB600 and HSB800 have developed by a steel company POSCO in Korea (Lee et al., 2007). The HSB steels have higher performance characteristics, such as yield and tensile strength, weldability, cold formability, than those of conventional structural steels, such as SM400, SM490, SM520, etc. The minimum yield strength (0.2% proof stress) of HSB600 and HSB800 is 450 MPa and 690 MPa, respectively, and the minimum tensile strength of HSB600 and HSB800 is 600 MPa and 800 MPa, respectively. HSB Steels do not have an obvious yield point and perfect plastic region before strain hardening process in the stress-strain curves as shown in Fig. 1. These steels are included in the steel bridge design codes in 2012 (MOLIT, 2012).

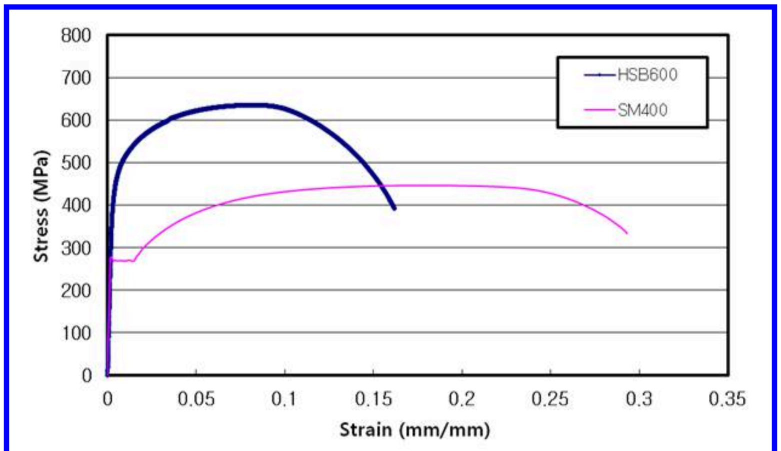

Fig. 1 Stress-strain curves of SM400 and HSB600

The high strength concrete is also included in the concrete bridge design codes in 2012 (MOCT). The maximum compressive strength of concrete is limited to 70 MPa. The stress-strain curves of concrete are also introduced for nonlinear analysis or design of the concrete structures. Fig. 2 shows the stress-strain curves for design of the concrete structures. The ultimate compressive strain of concrete is a fixed value of 0.0033 mm/mm for concrete with the strength up to 40 MPa concrete and 0.003 mm/mm for 70 MPa concrete. The ultimate concrete strain between 40 MPa and 70 MPa concrete can be determined by linear interpolation. In case of steel-concrete composite columns 100MPa high-performance concrete can be applied.

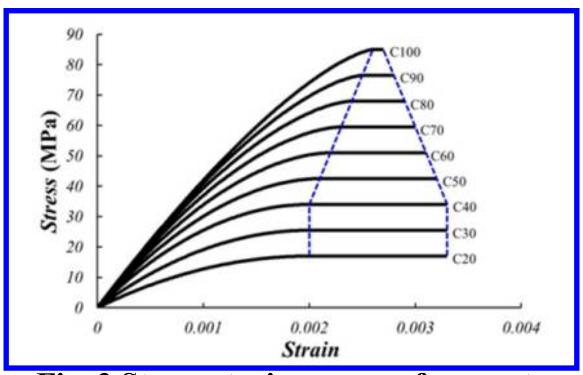

Fig. 2 Stress-strain curves of concrete

The ultimate flexural strength of composite girders at sagging bending is influenced by the material characteristics of steels and concrete. The cross-section details of composite girders also influence on the ductility and the ultimate flexural capacity of composite girders. The moment capacity of composite sections in sagging bending may be determined by simple plastic theory. The simple plastic theory requires composite sections to be ductile to show sufficient rotation and moment capacity greater than plastic moment. For brittle composite sections, the moment capacity is governed by premature concrete crushing and thus, the bending resistance should be reduced for ensuring additional safety margin. In the codes of AASHTO LRFD (2007) and Eurocode 4 (2005), strength reduction factors and ductility requirements are also introduced.

In composite bridges, steel girders may be designed by homogeneous sections (conventional composite girder) or hybrid sections (hybrid composite girder). In hybrid composite girders in sagging bending region HSB steels may be used only at the tension flange because the tension flange contributes most of the ultimate flexural strength to the hybrid composite girders. The minimum compressive strength of the cast-in-place concrete for bridge deck is 27 MPa. For precast concrete bridge decks 35 MPa may be used for post-tensioning. Different from composite columns of concrete filled steel tube columns or steel reinforced concrete columns, transverse cracks caused by hydration heat should be considered when high strength concrete applies in the cast-in-place concrete bridge decks. In addition the empirical design method based on the fatigue strength of concrete decks applies in Korea. This method adapts the minimum thickness of concrete bridge deck of 240 mm and the longitudinal reinforcement ratio, 0.006 at sagging bending region and 0.015 at hogging bending region. If high strength concrete applies at cast-in-place concrete decks, transverse cracks may be expected at early curing stage and these cracks affect the serviceability and the durability of concrete bridge decks.

In order to develop new design equations for predicting the nominal flexural strength of conventional composite girders and hybrid composite girders, the ultimate moment capacity and the ductility of a wide range of composite sections are investigated by using moment-curvature analyses and simple plastic theory.

STRENGTH REDUCTION FACTOR

For the safety of brittle composite sections, the ultimate moment capacity of composite girders should be reduced to introduce additional safety margin. In the AASHTO LRFD (2007), the nominal flexural strength at the ductility limit, $D_p / D_t = 0.42$, is regulated to $0.78 M_p$ for conventional composite girders. D_t represents the total height of composite section and D_p is the depth of plastic neutral axis in composite section. The lower boundary values of the ultimate moment capacity at $D_p / D_t = 0.42$ are close to $0.96 M_p$ as shown in Fig. 3. It means the addition safety margin is 1.23 for $0.96 M_p$ or 1.28 for the plastic moment M_p as shown in Fig. 4 (Youn et al., 2013). These values of 1.23 and 1.28 are related to the research results conducted by Ansourian (1982) and Wittry (1993).

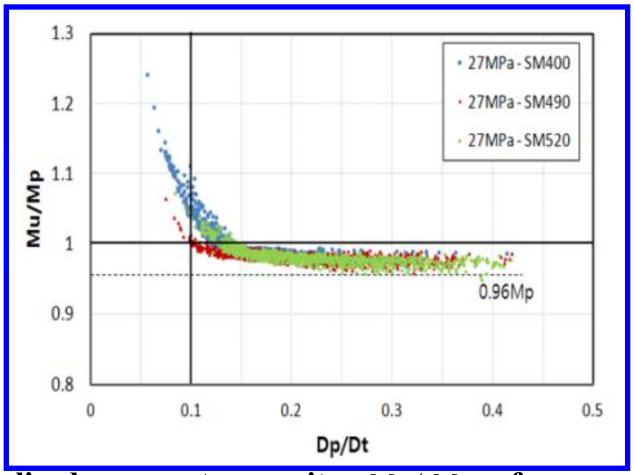

Fig. 3 Normalized moment capacity M_u / M_p of conventional composite girders

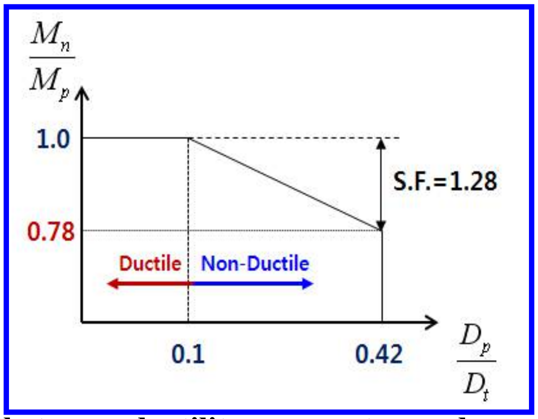

Fig. 4 Relationship between ductility parameter and moment capacity in the AASHTO LRFD (2007)

Wittry assumed the ultimate moment capacity of brittle composite girders linearly decreases from the plastic moment M_p to the yield moment M_y as the ratio of D_p / D' changes from 1 to 5 and proposed new design equation for brittle composite sections with additional strength reduction factor ϕ=0.85 at D_p / D' = 5 as shown in Eq. 1 and Fig. 5.

$$M_n = \frac{5M_p - \phi M_y}{4} + \frac{\phi M_y - M_p}{4}\left(\frac{D_p}{D'}\right), \quad 1 \le D_p / D' \le 5 \tag{1}$$

where D' is the depth of maximum plastic neutral axis for ductile conventional composite girders proposed by Wittry. D' is $0.7(D_t / 7.5)$ for 345 MPa composite section and $0.9(D_t / 7.5)$ for 250 MPa composite section.

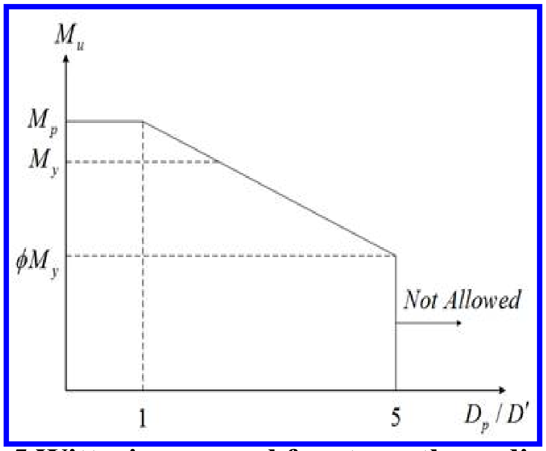

Fig. 5 Wittry's proposal for strength prediction

When the ductility limit $D_p / D' = 5$ in Wittry's equation is used, the actual ductility limit changes with varied steel grades and the ultimate curvature of cross-section at the ductility limit is not same to that at the ductility limit $D_p / D_t = 0.42$. Furthermore the ultimate moment capacity of brittle composite sections does not linearly decreases from the plastic moment to the yield moment as the ductility ratio D_p / D' changes and also the steel grade changes as shown in Fig. 6 and Fig. 7 (Youn et al., 2013).

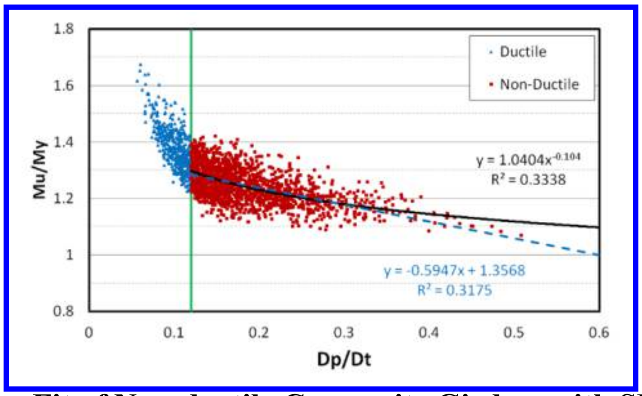

Fig. 6 Curve Fit of Non-ductile Composite Girders with SM400 Steel

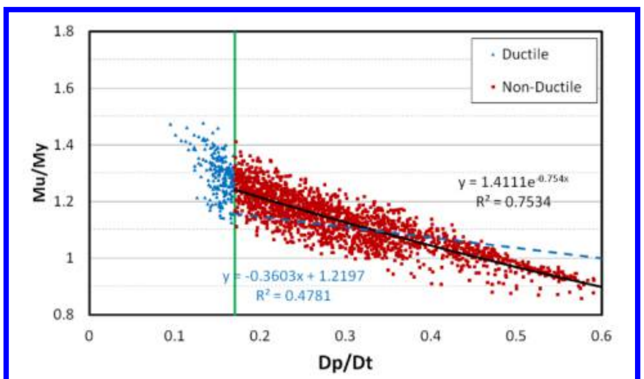

Fig. 7 Curve Fit of Non-ductile Composite Girders with HSB600 Steel

The values of M_u / M_y at $D_p / D_t = 0.42$ are summarized in Table 1. Therefore there are some needs to change the addition safety margin of 1.23 for $0.96 M_p$ or 1.28 for the plastic moment for consistency to varied steel grades.

Table 1 M_u / M_y **at** $D_p / D_t = 0.42$

	SM400	SM490	SM520	Average	HSB600	HSB800
M_u / M_y	1.139	1.099	1.063	1.100	1.028	0.889

Concrete stress-strain model presented in the Comitè Europèen du Bèton (1991) is applied as shown in Eq. 2 and material properties of steels are summarized in Table 2.

$$f_c = \frac{0.85 f_{ck}(a - 206,600\varepsilon_c)\varepsilon_c}{1 + b\varepsilon_c} \tag{2}$$

where, $a = 39,000(0.85 f_{ck} + 7.0)^{-0.953}$

$b = 65,600(0.85 f_{ck} + 10.0)^{-1.085} - 860$

Table 2 Material properties of steels

Property	SM400	SM490	SM520	HSB600	HSB800
Yield strength (MPa)	240	320	360	450	690
Tensile strength (MPa)	400	490	520	600	800
Yield strain (mm/mm)	0.00117	0.00157	0.00175	0.00221	0.00336
Strain-hardening strain (mm/mm)	0.016	0.020	0.015	0.00221	0.00336
Elastic modulus (MPa)	205,000	205,000	205,000	205,000	205,000
Modulus of strain-hardening region (MPa)	4,800	3,800	4500	4,455	3,222

MODIFIED WITTRY'S EQUATION

The nominal flexural strength of brittle composite girders shown in the equation (1) is modified to obtain new strength equation as a function of the ductility parameter D_p / D_t. For example, as shown in Eq. 3, a modified strength equation for composite sections with SM400 steel can be obtained as same as the process of Wittry's equation (see Eq. 1).

$$M_n = \frac{0.42M_p - 0.12\varphi 1.139M_y}{0.30} + \frac{\varphi 1.139M_y - M_p}{0.30}\left(\frac{D_p}{D_t}\right), \quad 0.12 \le D_p / D_t \le 0.42 \qquad (3)$$

Fig. 8 shows the comparison of the ultimate flexural capacity and Eq. 3 of a wide range of brittle composite sections to obtain safety factor at the ductility limit $D_p / D_t = 0.42$. From the Fig. 8 the safety factor of 1.18 can be obtained at the ductility limit, $D_p / D_t = 0.42$ (Youn et al., 2013).

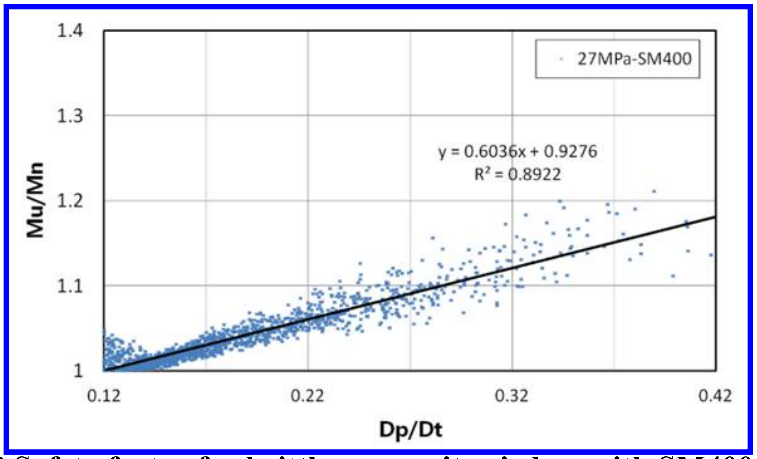

Fig. 8 Safety factor for brittle composite girders with SM400 Steel

For conventional composite sections with SM490 and SM520, safety factors at the ductility limit $D_p / D_t = 0.42$ are very close to 1.18. Using the safety factor ~~of~~ 1.18, the predicting equation for nominal flexural strength can be developed as show in Eq. 4 and Eq. 5. Fig. 9 shows the comparison of the proposed new design equation and the predicting strength equation in the AASHTO LRFD (2007). From the Fig. 9 it can be found that the safety factor at $D_p / D_t = 0.42$ is 1.18 for the plastic moment and 1.13 for $0.96\,M_p$.

$$D_p / D_t \le 0.1 \ : \qquad M_n = M_p \qquad (4)$$

$$0.1 \le D_p / D_t \le 0.42\,, \quad M_n = M_p(1.047 - 0.47\frac{D_p}{D_t}) \qquad (5)$$

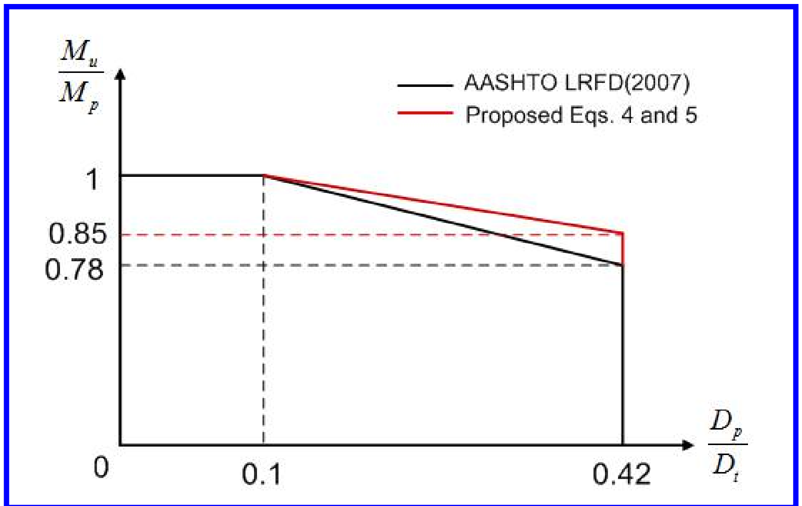

Fig. 9 Comparison of Proposed Equation and AASHTO LRFD's Strength Prediction

For conventional composite sections with HSB600 or HSB800, Wittry's method is not compatible for developing strength equations because M_u / M_n does not show linear distribution as shown in Fig. 10. Therefore in cases of HSB600 or HSB800 the safety factor of 1.13 for the ultimate moment capacity is directly used for developing new design equations as shown in Eq. 6 and Eq. 7. Fig. 11 show the proposed strength reduction factors for conventional composite girders with HSB600 and HSB800.

For conventional composite section with HSB600 ;

$$0.1 \le D_p / D_t \le 0.42\,,\quad M_n = M_p(1.056 - 0.56\frac{D_p}{D_t}) \qquad (6)$$

For conventional composite section with HSB800 ;

$$0.1 \le D_p / D_t \le 0.42\,,\quad M_n = M_p(1.091 - 0.91\frac{D_p}{D_t}) \qquad (7)$$

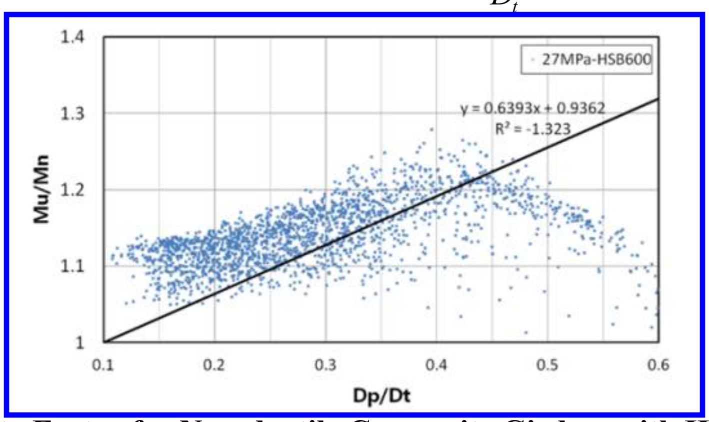

Fig. 10 Safety Factor for Non-ductile Composite Girders with HSB600 Steel

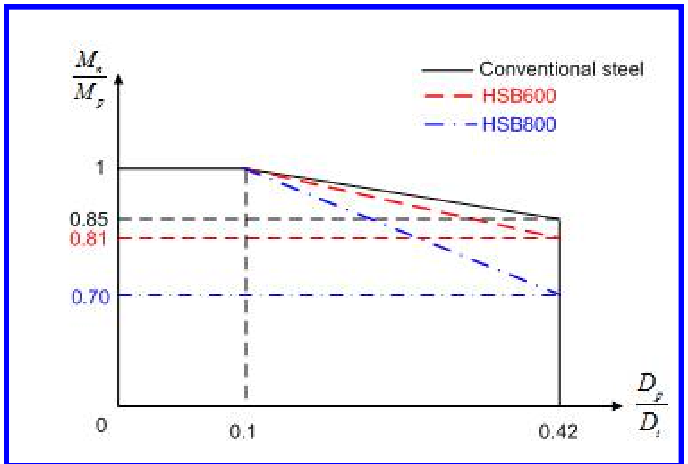

Fig. 11 Proposed Strength Equations of Conventional Composite Girders with HSB Steels

HYBRID COMPOSITE GIRDER

Hybrid composite girders can be applied in steel and concrete composite bridges and simple plastic theory also can be applied to calculate the collapse load of simple-supported or continuous composite girders. Ductile hybrid composite sections are to be ductile to show that the ultimate moment capacity is greater than its plastic moment as shown in Fig. 12 (Youn, 2013).

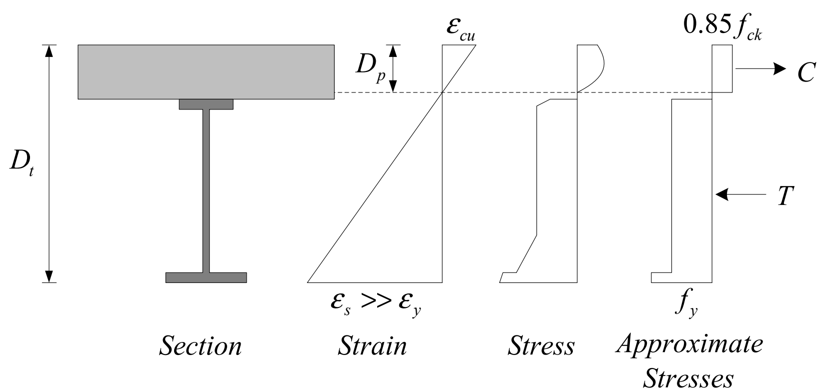

Fig. 12 Stress and strain distribution of hybrid composite section

For brittle hybrid composite sections, the ultimate moment capacity should be also reduced to obtain additional safety margin as same as that of conventional composite sections. In addition previous experimental tests conducted by Youn et al. (2008) suggest that the ultimate moment capacity of hybrid composite sections using HSB600 is greater than the predicting equations for the nominal flexural strength in the AASHOTO LRFD (2007).

Fig. 13 shows the normalized ultimate moment capacity of a wide range of hybrid composite sections with 27 MPa concrete deck according to the ductility parameter D_p / D^*. D^* represents the depth of maximum plastic neutral axis in the AASHTO bridge design codes (2000) and $D^* = D_t / 7.5$. The normalized ultimate moment capacity of hybrid composite sections is quite higher than the plastic moment M_p up to high ductility parameter D_p / D^* and thus, there are some needs to change the value of ductility parameter for classifying ductile or brittle hybrid composite sections. In addition it can be found that the ultimate moment capacity converges $0.96 M_p$ at $D_p / D_t = 0.42$ similar to that of conventional composite sections.

Ansourian (1982) proposed the minimum ductility parameter χ =1.4 is required for applying simple plastic theory to calculate the collapse load of simple-supported or continuous composite beams in sagging bending regions. This is same to the value of ductility parameter D_p / D_t = 0.143. It means the ductility parameter D_p / D_t = 0.143 can be adapted for the criteria for classifying ductile or non-ductile hybrid composite section in plastic design. Rotation capacity of the hybrid composite section is not less than that of the conventional composite sections, because rotation capacity is proportioned to the ultimate curvature of composite sections and the ultimate curvature depends on the ductility parameter of D_p / D_t. Therefore the additional safety margin for brittle hybrid composite sections can be introduced by dividing the ultimate moment capacity with the safety factor. The safety factor increases linearly from 1.0 at D_p / D_t=0.143 to 1.13 at D_p / D_t=0.42.

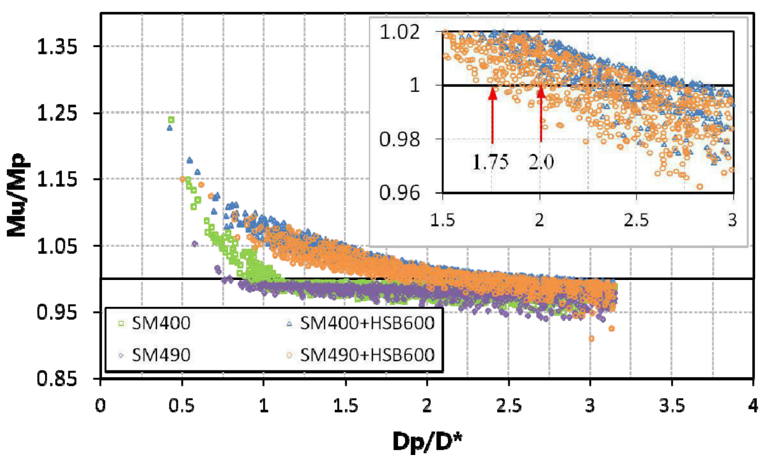

Fig. 13 Effect of hybrid steel combinations on ultimate moment capacity

For examples, the nominal flexural strength of hybrid composite sections with HSB600 can be proposed by using the safety factor of 1.13 at D_p / D_t=0.42 (Youn, 2013) as follows ;

For SM400+HSB600 hybrid composite sections;

$$D_p / D_t \le 0.1 \; : \qquad M_n = 1.08 M_p \tag{8}$$

$$0.1 \le D_p / D_t \le 0.42 : \; M_n = 1.08 M_p (1.067 - 0.67 \frac{D_p}{D_t}) \tag{9}$$

For SM490+HSB600 hybrid composite sections;

$$D_p / D_t \le 0.1 \ : \qquad M_n = 1.06 M_p \tag{10}$$

$$0.1 \le D_p / D_t \le 0.42 : \ M_n = 1.06 M_p (1.062 - 0.62 \frac{D_p}{D_t}) \tag{11}$$

where, M_p is the plastic moment of the hybrid composite sections with HSB600 high-performance steel at tension flange only.

In the previous equations, the maximum nominal flexural strength of $1.08M_p$ and $1.06M_p$ can be changed to the plastic moment M_p, and also the criteria of the ductility parameter for dividing ductile girders or brittle girders ~~also~~ can be changed from D_p / D_t=0.1 to D_p / D_t=0.15. In addition, steel combinations of hybrid composite sections can be changed and thus, it is considered that regulating predicting equations for each several hybrid composite section is not compatible to introduce in the design codes of steel and concrete composite structures. The research program is still running in order to propose simple predicting equations for calculating the nominal flexural strength of hybrid composite sections with HSB600 and HSB800.

SUMMARY AND CONCLUSIONS

In October 2011, the Korean Government has started a research project to develop the new design code for steel and concrete composite structures based on limit state design concepts. In 2013, the Korean Government starts to change the current Korean codes system to a set of new design codes system for whole infrastructures. This system will be similar to the Eurocodes's system. This paper presents a parametric study for the development of the nominal flexural strength of conventional composite girders and hybrid composite girders using HSB high-performance steels. In order to introduce HSB steels in the new steel and concrete design codes, the ultimate flexural strength and the ductility of a wide range of brittle composite girders are calculated by using moment-curvature analyses. The results of this research project for developing new design codes for steel-concrete composite structures are expected to the part of new design codes system.

ACKNOWLEDGEMENT

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