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著者	Toma, Shouji; Maeda, Jun-ya
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研究論文

Optimum Girder Height and Minimum Sectional Area of Highway Composite Girder Bridge

Shouji Toma* and Jun-ya Maeda**

Contents

1. Introduction

Selection of web size is the most fundamental factor in the girder bridge design. Especially, the girder height (web depth) affects the entire design of the girder such as web thickness, flange areas, stiffness of girder, etc. The girder height should be decided most carefully and appropriately.

The benchmark design project for highway composite girder bridges has been proposed (Toma and Duan 2007) and studied previously by comparing the ten designs participated from the world (Toma and Maeda 2010). As a result, it was found that many countries tended to use low girder height (web depth) without stiffeners.

This paper studies to find the optimum girder height by comparing the girder sections for various girder heights (web depths) so as to minimize the sectional area. The Specifications for Highway Bridges in Japan (JSHB) (JRA 2002) is applied in this study. Computer program used in this paper is "Preliminary Design of Composite Girder Bridge" developed by JIP Techno Science Inc. The designs in this paper may be considered as a benchmark to be provided in order to investigate the optimum design.

2. Design Criteria

The design criteria are set the same as the benchmark project except the span length (Toma and Maeda 2010), which are

(1) Span length L＝20m, 30m and 40m

* Professor, Civil and Environmental Engineering, Graduate School of Engineering, Hokkai-Gakuen University
** Former Master Student, Civil and Environmental Engineering, Graduate School of Engineering, Hokkai-Gakuen University

(2) Road width＝8.5m
(3) Support conditions - simply supported
(4) Number of girders＝4
(5) Thickness of concrete slab＝0.24m
(6) Thickness of asphalt pavement＝0.08m
(7) Weight of curb (base for hand rail)＝4.85kN/m
(8) Weight of hand rail (or barrier)＝0.5kN/m
(9) Weight of steel girder (exterior and interior)＝2.0kN/m for L＝20m, 3.3kN/m for L＝30m and 4.0kN/m for L＝40m
(10) Weight of haunch (exterior and interior girders)＝1.5kN/m
(11) Weight of form work＝1.0kN/m² (per unit road area, to be removed for composite section after the concrete slab hardened)

Figure 1 shows the general plan of the highway composite girder bridge studied in this paper. Table 1 shows the study cases for various span length and girder height with and without stiffeners. The span length is taken for three cases: 20m, 30m and 40m. The appropriate strength of steel is used in the designs: SM400 (the yield strength 235N/mm²) and SM490 (the yield strength 315N/mm²) for L＝20m, SM490 for L＝30m and SM490Y (the yield strength 355N/mm²) for L＝40m. The girder spacing is taken 2.6m which is the same as the benchmark study (Toma and Maeda 2010). The same dead loads including the slab are used in all design cases except the girder weight.

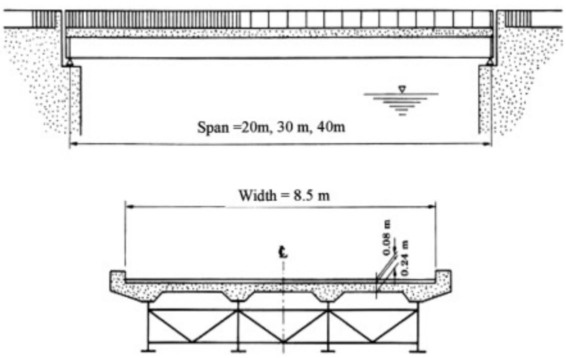

Figure 1　General Plan

3. Web Thickness and Stiffener Requirements

Web designs and stiffener requirements of ten designs from the world are investigated in the benchmark project (Toma and Maeda 2010). It was found that the horizontal (longitudinal) stiffener would not be required in most designs except three countries out of the ten. The vertical (transverse) stiffener would be needed in many of the designs. The study also revealed there was a sufficient margin to the deflection limit, which meant the stiffness of girder did not control the design. Now, it is worthwhile to study the optimum girder height in conjunction with the stiffener requirements. When the stiffeners are used to prevent web buckling, the web thickness can be small. However, it results in the increase of fabrication cost, on the other hand the decrease of material cost.

4. Optimum Girder Height for Span Length L＝20m

4.1 Optimum Girder Height

Design comparison is made when thicker web is used by neglecting vertical and horizontal stiffeners than the previous benchmark

Table 1　Girder Height and Stiffeners for Study Cases

Stiffeners / Span	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
	×	×	×	○	○	○
20m	800〜1400mm		800〜1300mm			
30m	900〜1600mm		1200〜1700mm		1400〜2000mm	
40m			1500〜2100mm		1700〜2300mm	

×: no stiffener, ○: with stiffener

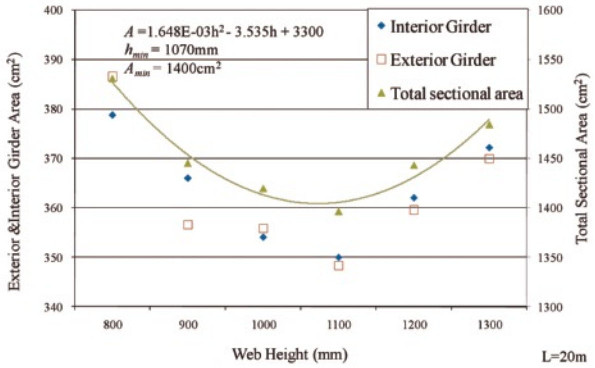

Figure 2 Optimum Girder Height for L=20m (no stiffeners, SM400)

design (Toma and Maeda 2010). Table 2 shows the design results of exterior and interior girder sections for various web heights (depths) when the steel material SM400 (the yield strength 235N/mm²) and no stiffeners are used. The girder height (web depth) varies from 800 to 1300mm. Sectional areas of the exterior and interior girders and total area of the four girders are plotted in Fig. 2.

The total sectional areas can be approximated by a second order polynomial equation with respect to the girder height. The equation is expressed as follows:

$$A=0.001648h^2-3.535h+3300 \quad (1)$$

in which A=total area of 4 girders (cm²), h=web height (mm)

The optimum girder height is obtained by differentiating Eq. (1).

$$\frac{\partial A}{\partial h}=0.003296h-3.535=0 \quad (2)$$

$$h=1070mm$$

The derivative of the approximation equation gives the optimum girder height h_{min}=1070mm and the minimum sectional area A_{min}=1400cm² as can be seen in Fig. 2. The ratio of the optimum height to the span length is calculated as h_{min}/L=18.7 in this case.

Table 3 and Figure 3 show the design results when the steel material SM490 (the yield strength 315N/mm²) and no stiffeners are used. Similarly to Fig. 2, the optimum girder

Table 2 Design Results for L=20m (no stiffeners, SM400)

	Web Height (mm)	800	900	1000	1100	1200	1300
Interior Girder	Top-Flange	400＊18	360＊16	320＊13	280＊11	260＊10	240＊10
	(Sectional area cm²)	(72)	(58)	(42)	(31)	(26)	(24)
	Web	800＊12	900＊13	1000＊15	1100＊16	1200＊18	1300＊19
	(Sectional area cm²)	(96)	(117)	(150)	(176)	(216)	(247)
	Bottom-Flange	620＊34	580＊33	560＊29	530＊27	500＊24	440＊23
	(Sectional area cm²)	(211)	(191)	(162)	(143)	(120)	(101)
	Sectional area (cm²)	379	366	354	350	362	372
	Is (cm⁴)	448,200	508,400	551,400	611,700	711,900	823,200
	Iv (cm⁴)	1,962,000	2,259,000	2,493,000	2,782,000	3,069,000	3,368,000
	Deflection δ_L (mm)	12.4	11.1	9.9	8.9	8.0	7.3
	Deflection δ_d (mm)	44.3	39.7	36.4	32.9	28.5	24.7
Exterior Girder	Top-Flange	420＊19	370＊17	330＊14	290＊11	260＊10	240＊10
	(Sectional area cm²)	(80)	(63)	(46)	(32)	(26)	(24)
	Web	800＊12	900＊13	1000＊15	1100＊16	1200＊18	1300＊19
	(Sectional area cm²)	(96)	(117)	(150)	(176)	(216)	(247)
	Bottom-Flange	620＊34	570＊31	570＊28	540＊26	490＊24	430＊23
	(Sectional area cm²)	(211)	(177)	(160)	(140)	(118)	(99)
	Sectional area (cm²)	387	357	356	348	360	370
	Is (cm⁴)	472,900	514,200	569,000	613,000	706,900	816,900
	Iv (cm⁴)	1,893,000	2,072,000	2,384,000	2,663,000	2,937,000	3,223,000
	Deflection δ_L (mm)	10.5	9.4	8.4	7.6	6.9	6.3
	Deflection δ_d (mm)	47.0	42.0	38.7	35.3	30.9	26.8
Total sectional area (cm²)		1531	1445	1420	1396	1443	1484

Table 3　Design Results for L＝20m (no stiffeners, SM490)

Web Height (mm)		700	800	900	1000	1100	1200
Interior Girder	Top-Flange	350＊16	330＊13	290＊13	250＊14	240＊13	240＊11
	(Sectional area cm²)	(58)	(43)	(38)	(35)	(31)	(26)
	Web	700＊12	800＊14	900＊15	1000＊17	1100＊19	1200＊20
	(Sectional area cm²)	(84)	(112)	(135)	(170)	(209)	(240)
	Bottom-Flange	540＊33	480＊32	480＊27	460＊23	360＊24	320＊22
	(Sectional area cm²)	(178)	(154)	(130)	(106)	(86)	(70)
	Sectional area (cm²)	320	309	302	311	327	337
	Is (cm⁴)	281,200	326,600	387,400	465,929	550,500	619,700
	Iv (cm⁴)	1,414,000	1,625,000	1,807,000	2,007,000	2,257,000	2,485,000
	Deflection δ_L (mm)	17.6	15.4	13.7	12.1	11.0	10.0
	Deflection δ_d (mm)	71.0	61.6	52.2	44.5	36.9	33.0
Exterior Girder	Top-Flange	360＊17	350＊13	290＊13	250＊14	230＊14	240＊11
	(Sectional area cm²)	(61)	(46)	(38)	(35)	(32)	(26)
	Web	700＊12	800＊14	900＊15	1000＊17	1100＊19	1200＊20
	(Sectional area cm²)	(84)	(112)	(135)	(170)	(209)	(240)
	Bottom-Flange	550＊32	480＊31	470＊27	460＊23	360＊23	310＊21
	(Sectional area cm²)	(176)	(149)	(127)	(106)	(83)	(65)
	Sectional area (cm²)	321	306	300	311	324	332
	Is (cm⁴)	292,700	330,600	384,600	465,929	546,600	610,400
	Iv (cm⁴)	1,354,000	1,541,000	1,729,000	1,943,000	2,146,000	2,366,000
	Deflection δ_L (mm)	14.8	12.9	11.6	10.4	9.4	8.5
	Deflection δ_d (mm)	74.9	65.5	56.4	47.4	40.3	35.9
Total sectional area (cm²)		1282	1230	1204	1243	1301	1337

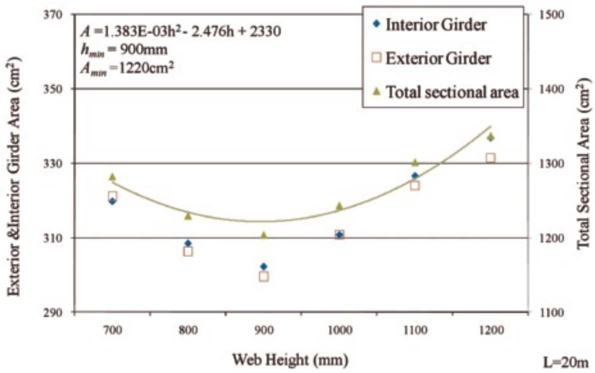

Figure 3　Optimum Girder Height for L＝20m (no stiffeners, SM490)

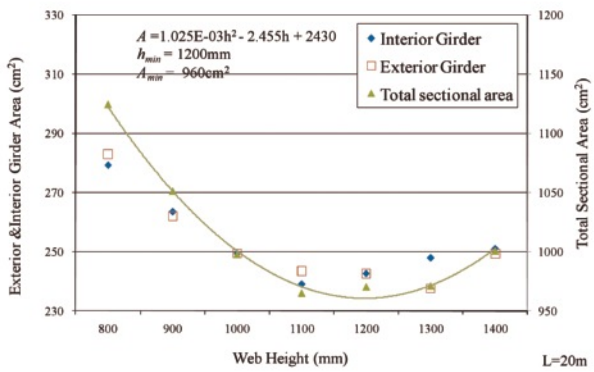

Figure 4　Optimum Girder Height for L＝20m (with vertical stiffener, SM490)

height and the corresponding minimum sectional area are obtained as shown in Fig. 3. As higher strength of material is used than the previous case, the optimum depth and the corresponding minimum sectional area are smaller. It should be pointed out that the web thickness for higher strength of steel must be larger than lower strength of steel because the web with higher strength will be subjected to higher stress which may increase the possibility of shear buckling.

Table 4 and Figure 4 show the design results when the steel material SM490 (the yield strength 315N/mm²) and the vertical (transverse) stiffener are used. When the vertical stiffener is used to prevent shear buckling, the web thickness can be thinner, which results in more economical girder sections. The opti-

Table 4 Design Results for L＝20m (with vertical stiffener, SM490)

	Web Height (mm)	800	900	1000	1100	1200	1300	1400
Interior Girder	Top-Flange	320＊16	320＊14	310＊12	290＊11	260＊11	230＊13	220＊13
	(Sectional area cm^2)	(51)	(45)	(37)	(32)	(29)	(30)	(29)
	Web	800＊9	900＊9	1000＊9	1100＊10	1200＊10	1300＊10	1400＊11
	(Sectional area cm^2)	(72)	(81)	(90)	(99)	(120)	(130)	(154)
	Bottom-Flange	520＊30	510＊27	470＊26	470＊23	470＊20	400＊22	360＊19
	(Sectional area cm^2)	(156)	(138)	(122)	(108)	(94)	(88)	(68)
	Sectional area (cm^2)	279	264	249	239	243	248	251
	Is (cm^4)	323,600	372,800	414,800	461,800	532,600	636,600	706,700
	Iv (cm^4)	1,552,000	1,730,000	1,916,000	2,096,000	2,311,000	2,597,000	2,715,000
	Deflection δ_L (mm)	15.8	14.1	12.8	11.7	10.6	10.4	8.8
	Deflection δ_d (mm)	59.3	51.9	45.9	40.4	35.7	31.4	28.8
Exterior Girder	Top-Flange	320＊17	310＊14	310＊12	260＊14	260＊11	230＊13	230＊11
	(Sectional area cm^2)	(54)	(43)	(37)	(36)	(29)	(30)	(25)
	Web	800＊9	900＊9	1000＊9	1100＊10	1200＊10	1300＊10	1400＊11
	(Sectional area cm^2)	(72)	(81)	(90)	(99)	(120)	(130)	(154)
	Bottom-Flange	540＊29	510＊27	470＊26	470＊23	470＊20	370＊21	350＊20
	(Sectional area cm^2)	(157)	(138)	(122)	(108)	(94)	(78)	(70)
	Sectional area (cm^2)	283	262	249	244	243	238	249
	Is (cm^4)	334,000	367,400	414,800	486,500	532,600	608,700	689,700
	Iv (cm^4)	1,506,000	1,680,000	1,863,000	2,041,000	2,251,000	2,365,000	2,676,000
	Deflection δ_L (mm)	12.8	11.5	10.3	9.5	8.7	7.2	7.4
	Deflection δ_d (mm)	61.7	55.3	48.7	42.4	38.2	35.5	30.9
Total sectional area (cm^2)		1124	1051	998	965	970	971	1001

mum girder height (web depth) is larger than the previous cases: thinner web will bear larger depth without having large sectional area, yet maintaining stiffness of girders. The horizontal (longitudinal) stiffener is not effective in this case because of the short span length. The horizontal stiffener is normally useful to reduce the sectional area of web when large stiffness thus large girder height is required for long spans.

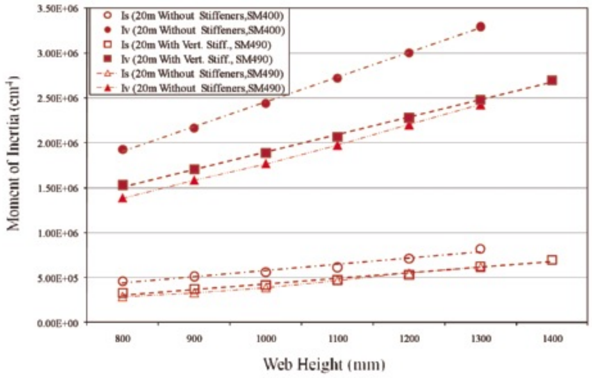

Figure 5 Moment of Inertia, L＝20m

4.2 Stiffness and Deflections

Figure 5 shows a comparison of the moment of inertia of the steel section I_s and the composite section I_v. It can be seen that the lower strength requires larger moment of inertia. The ratio of I_v to I_s lies between 4.0 to 4.5.

Deflections due to the live load are plotted in Fig. 6 for the exterior and interior girders. Since the flexural stiffness of girder depends on the moment of inertia of the cross section, it is inversely proportional to the deflection: the

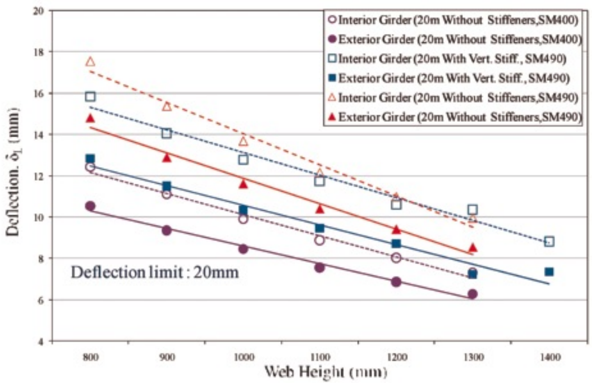

Figure 6 Deflections due to Live Load, L＝20m

larger moment of inertia, i.e., bending stiffness, in Fig. 5 results in smaller deflection in Fig. 6. According to JSHB (JRA 2002), the deflection limit for live load is calculated as 20 mm for the span length L＝20m, which is well above the calculated deflections in entire range of the web height in Fig 6.

5. Optimum Girder Height for Span Length L＝30m

5.1 Optimum Girder Height

In case of the span length L＝30m, the design results are given in Tables 5, 6 and 7 for different conditions of stiffeners; with no stiffeners, with vertical stiffener only and with both vertical and horizontal stiffeners, respectively. The sectional areas of girders are plotted in Figs. 7, 8 and 9 for each stiffener conditions. The steel material SM490 (the yield stress 315N/mm^2) is used in this case.

The optimum girder height which gives the minimum sectional area is shown in Figs. 7 to 9. As more stiffeners are used, the optimum girder height becomes large. For example, in case that no stiffeners are used (Table 5 and Fig. 7) the optimum girder height is 1285mm which is small comparing to other stiffener conditions. However, the web thickness is unrealistically large as can be seen in Table 5.

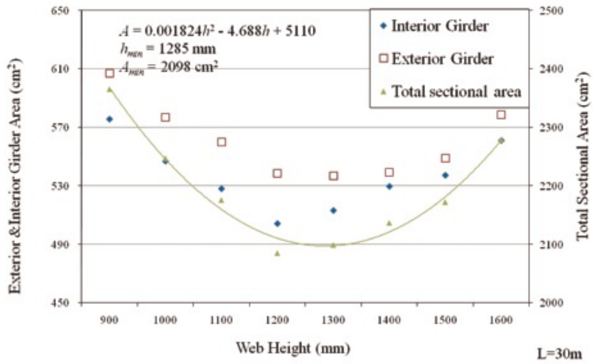

Figure 7 Optimum Girder Height for L＝30m (no stiffeners, SM490)

Table 5 Design Results for L＝30m (with no stiffeners, SM490)

Web Height (mm)		900	1000	1100	1200	1300	1400	1500	1600
Interior Girder	Top-Flange	520＊23	480＊20	390＊19	340＊18	340＊14	300＊15	320＊11	330＊10
	(Sectional area cm^2)	(120)	(96)	(74)	(61)	(48)	(45)	(35)	(33)
	Web	900＊16	1000＊17	1100＊19	1200＊20	1300＊22	1400＊24	1500＊25	1600＊27
	(Sectional area cm^2)	(144)	(170)	(209)	(240)	(286)	(336)	(375)	(432)
	Bottom-Flange	520＊60	520＊54	510＊48	520＊39	460＊39	450＊33	470＊27	400＊24
	(Sectional area cm^2)	(312)	(281)	(245)	(203)	(179)	(149)	(127)	(96)
	Sectional area (cm^2)	576	547	528	504	513	530	537	561
	Is (cm^4)	916,000	993,000	1,064,000	1,139,000	1,259,000	1,432,000	1,552,000	1,721,000
	Iv (cm^4)	3,222,000	3,607,000	3,960,000	4,182,000	4,644,000	5,004,000	5,438,000	5,797,000
	Deflection δ_L (mm)	28.8	25.8	23.4	22.3	19.3	18.4	18.2	15.9
	Deflection δ_d (mm)	120.9	109.8	102.6	96.9	85.9	79.2	76.2	63.7
Exterior Girder	Top-Flange	520＊25	480＊23	390＊22	340＊19	340＊13	300＊14	300＊12	300＊11
	(Sectional area cm^2)	(130)	(110)	(86)	(65)	(44)	(42)	(36)	(33)
	Web	900＊16	1000＊17	1100＊19	1200＊20	1300＊22	1400＊24	1500＊25	1600＊27
	(Sectional area cm^2)	(144)	(170)	(209)	(240)	(286)	(336)	(375)	(432)
	Bottom-Flange	520 ＊ 64	520 ＊ 57	520 ＊ 51	520 ＊ 45	480 ＊ 43	460 ＊ 35	460 ＊ 30	420 ＊ 27
	(Sectional area cm^2)	(333)	(296)	(265)	(234)	(206)	(161)	(138)	(113)
	Sectional area (cm^2)	607	577	560	539	537	539	549	578
	Is (cm^4)	984,000	1,070,000	1,165,000	1,225,000	1,301,000	1,451,000	1,605,000	1,812,000
	Iv (cm^4)	3,223,000	3,480,000	3,988,000	4,354,000	4,788,000	4,981,000	5,402,000	5,868,000
	Deflection δ_L (mm)	28.8	26.1	23.3	22.1	19.2	18.3	18.3	15.9
	Deflection δ_d (mm)	125.5	114.1	106.2	101.0	89.8	82.6	79.6	66.0
Total sectional area (cm^2)		2365	2247	2176	2085	2099	2137	2172	2279

Table 6　Design Results for L＝30m (with vertical stiffener, SM490)

	Web Height (mm)	900	1000	1100	1200	1300	1400	1500	1600	1700
Interior Girder	Top-Flange	470＊29	460＊25	460＊22	400＊22	400＊19	330＊19	320＊16	300＊16	290＊14
	(Sectional area cm^2)	(136)	(115)	(101)	(88)	(76)	(63)	(51)	(48)	(41)
	Web	900＊9	1000＊9	1100＊9	1200＊10	1300＊10	1400＊11	1500＊12	1600＊13	1700＊14
	(Sectional area cm^2)	(81)	(90)	(99)	(120)	(130)	(154)	(180)	(208)	(238)
	Bottom-Flange	550＊58	550＊52	550＊47	520＊45	520＊38	500＊36	510＊35	500＊30	460＊28
	(Sectional area cm^2)	(319)	(286)	(259)	(234)	(198)	(180)	(179)	(150)	(129)
	Sectional area (cm^2)	536	491	459	442	404	397	410	406	407
	Is (cm^4)	932,000	999,000	1,087,000	1,189,000	1,231,000	1,314,000	1,448,000	1,582,000	1,689,000
	Iv (cm^4)	3,151,000	3,469,000	3,799,000	4,170,000	4,296,000	4,697,000	5,397,000	5,612,000	5,947,000
	Deflection δ_L (mm)	29.0	26.5	24.3	22.2	21.4	19.6	18.3	17.0	15.8
	Deflection δ_d (mm)	119.8	110.0	102.3	94.7	90.2	84.3	76.2	67.2	67.1
Exterior Girder	Top-Flange	520＊29	500＊25	500＊22	430＊22	430＊19	370＊19	320＊17	300＊15	290＊14
	(Sectional area cm^2)	(151)	(125)	(110)	(95)	(82)	(70)	(54)	(45)	(41)
	Web	900＊9	1000＊9	1100＊9	1200＊10	1300＊10	1400＊11	1500＊12	1600＊13	1700＊14
	(Sectional area cm^2)	(81)	(90)	(99)	(120)	(130)	(154)	(180)	(208)	(238)
	Bottom-Flange	550＊63	550＊55	550＊50	520＊49	520＊44	510＊38	510＊34	500＊32	500＊29
	(Sectional area cm^2)	(347)	(303)	(275)	(255)	(229)	(194)	(173)	(160)	(145)
	Sectional area (cm^2)	578	518	484	469	441	418	408	413	424
	Is (cm^4)	1,023,000	1,070,000	1,164,000	1,273,000	1,346,000	1,416,000	1,464,000	1,588,000	1,761,000
	Iv (cm^4)	3,220,000	3,480,000	3,829,000	4,267,000	4,577,000	4,763,000	5,122,000	5,616,000	6,097,000
	Deflection δ_L (mm)	29.4	26.5	24.4	22.3	21.5	19.6	18.2	16.7	15.3
	Deflection δ_d (mm)	124.2	114.2	106.0	98.1	93.4	87.2	79.7	70.3	69.7
Total sectional area (cm^2)		2229	2017	1885	1823	1688	1630	1635	1638	1662

Table 7　Design Results for L＝30m (with vert. & horiz. stiffs, SM490)

	Web Height (mm)	1400	1500	1600	1700	1800	1900	2000
Interior Girder	Top-Flange	330＊17	320＊19	310＊18	310＊18	310＊18	300＊18	300＊18
	(Sectional area cm^2)	(56)	(61)	(56)	(56)	(56)	(54)	(54)
	Web	1400＊9	1500＊9	1600＊9	1700＊9	1800＊9	1900＊9	2000＊10
	(Sectional area cm^2)	(126)	(135)	(144)	(153)	(162)	(171)	(200)
	Bottom-Flange	530＊31	530＊32	510＊30	480＊30	450＊29	450＊27	440＊24
	(Sectional area cm^2)	(164)	(170)	(153)	(144)	(131)	(122)	(106)
	Sectional area (cm^2)	346	365	353	353	348	347	360
	Is (cm^4)	1,154,000	1,407,000	1,539,000	1,691,000	1,802,000	1,916,000	1,916,000
	Iv (cm^4)	4,284,000	4,989,000	5,351,000	5,731,000	6,120,000	6,595,000	6,595,000
	Deflection δ_L (mm)	20.7	18.6	17.5	16.7	15.3	14.2	14.2
	Deflection δ_d (mm)	86.2	78.2	73.2	70.6	64.2	60.5	60.5
Exterior Girder	Top-Flange	360＊25	330＊20	310＊19	290＊18	310＊15	290＊17	290＊17
	(Sectional area cm^2)	(90)	(66)	(59)	(52)	(47)	(49)	(49)
	Web	1400＊9	1500＊9	1600＊9	1700＊9	1800＊9	1900＊9	2000＊10
	(Sectional area cm^2)	(126)	(135)	(144)	(153)	(162)	(171)	(200)
	Bottom-Flange	550＊39	530＊34	520＊33	510＊30	500＊29	470＊28	450＊26
	(Sectional area cm^2)	(215)	(180)	(172)	(153)	(145)	(132)	(117)
	Sectional area (cm^2)	431	381	375	358	354	352	366
	Is (cm^4)	1,584,000	1,491,000	1,593,000	1,684,000	1,782,000	1,898,000	1,898,000
	Iv (cm^4)	4,980,000	5,032,000	5,504,000	5,754,000	6,231,000	6,631,000	6,631,000
	Deflection δ_L (mm)	19.5	18.4	16.9	15.5	14.8	14.0	14.0
	Deflection δ_d (mm)	85.7	81.4	75.8	71.1	67.2	63.6	63.6
Total sectional area (cm^2)		1554	1493	1455	1422	1404	1397	1452

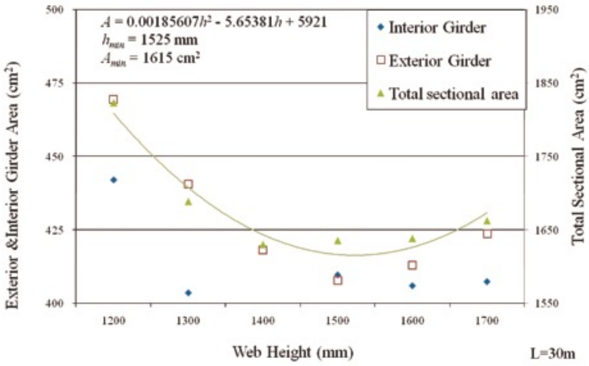

Figure 8 Optimum Girder Height for L＝30m (with vertical stiffener, SM490)

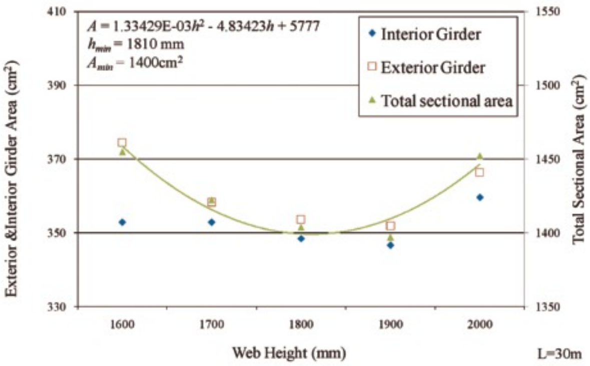

Figure 9 Optimum Girder Height for L＝30m (with vert. & horiz. stiffs., SM490)

For example, the minimum thickness for web height 1600mm is 27mm which is about 2 times of the thickness 13mm for the case with vertical stiffener. This concludes that in the case of large web height the design of neglecting the vertical stiffener is not realistic. Therefore, at least the vertical stiffener should be used to have practical design as shown in Table 6 and Fig. 8. The optimum height h＝1285mm gives the ratio to the span length h_{min}/L＝23.3.

When both vertical and horizontal stiffeners are used as shown in Table 7 and Fig. 9, the sectional area becomes small comparing to other cases but the number of structural components increases which will cause more fabrication cost. The minimum thickness of steel plate is taken 9mm in this case.

In conclusion, the use of vertical stiffener but no horizontal stiffener as shown in Table 6 and Fig. 8 is recommendable for the span

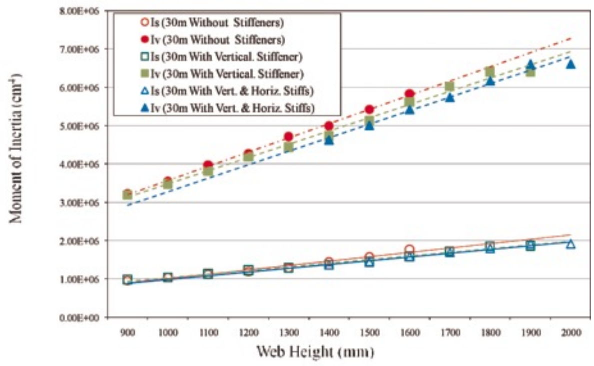

Figure 10 Moment of Inertia, L＝30m

length L＝30m. The optimum height h＝1525mm gives the ratio to the span length h_{min}/L＝19.7. When the web height is lower than the optimum height, the increase of flange areas is more than the decrease of web area and consequently the total area gradually increases. When the web height is larger than the optimum height, the increase of web area is more than the decrease of flange areas.

5.2 Stiffness and Deflections

Moment of inertia of the external and internal girders for the steel section, I_s, and the composite section, I_v, are plotted in Fig. 10 when the girder height varies. It can be seen that the moment of inertia is proportional with respect to the girder height. From Fig. 10, it is found that the ratio of the moment of inertia of the composite girder to the steel girder lies in a narrow range from 3.3 to 3.6. This ratio is smaller than the span length L＝20m which is given as 4.0 to 4.5 in Section 4.2. This is because the same slab sizes are used in both designs.

The deflections due to the live are plotted in Fig. 11 which shows clear inverse proportion to the web height. As similarly to the span length L＝20m, the deflection limit 45mm for live load by JSHB (JRA 2002) for the span length 30m is away above the actual deflections. This implies that the deflection (stiffness) does not control the design.

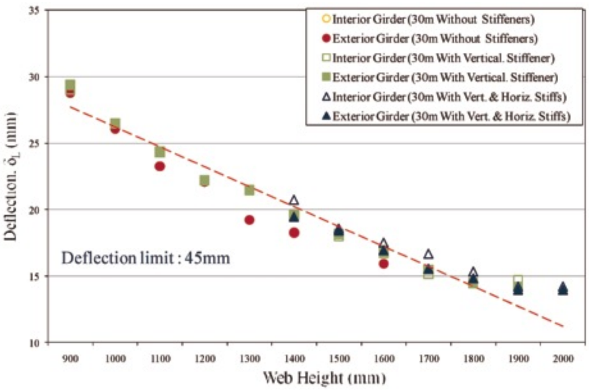

Figure 11　Deflections due to Live Load, L=30m

6. Optimum Girder Height for Span Length L=40m

6.1 Optimum Girder Height

In case of the span length L=40m, the design results are given in Tables 8 and 9 for two different conditions of stiffener; with vertical stiffener only and with both vertical and horizontal stiffeners, respectively. The sectional areas of girders are plotted in Figs. 12 and 13 for different stiffener conditions, correspondingly. The steel material SM490Y (the yield stress 355N/mm^2) is used in this case.

The optimum girder height which gives the minimum sectional area is shown in Figs. 12 and 13. As more stiffeners are used, the optimum girder height becomes large. For example, in case that only vertical stiffener is used (Table 8 and Fig. 12) the optimum girder height is 1830mm which gives the ratio to the span length h_{min}/L=21.9 for L=40m.

The web thickness will be unrealistically large for large span bridges if no stiffeners are used. Therefore, at least the vertical stiffener should be used to have practical design. When both vertical and horizontal stiffeners are used as shown in Table 9 and Fig. 13, the sectional area becomes small comparing to the design with vertical stiffener only, but the number of structural components increases which will cause more fabrication cost.

Table 8　Design Results for L=40m (with vertical stiffener, SM490Y)

	Web Height (mm)	1500	1600	1700	1800	1900	2000	2100
Interior Girder	Top-Flange	410*26	400*23	380*21	360*18	350*16	320*17	320*15
	(Sectional area cm^2)	(107)	(92)	(80)	(65)	(56)	(54)	(48)
	Web	1500*13	1600*14	1700*14	1800*15	1900*16	2000*17	2100*18
	(Sectional area cm^2)	(195)	(224)	(238)	(270)	(304)	(340)	(378)
	Bottom-Flange	660*43	640*37	610*36	630*32	620*30	580*28	560*26
	(Sectional area cm^2)	(284)	(237)	(220)	(202)	(186)	(162)	(146)
	Sectional area (cm^2)	585	553	537	536	546	557	572
	Is (cm^4)	2,352,000	2,414,000	2,542,000	2,661,000	2,871,000	3,140,000	3,382,000
	Iv (cm^4)	7,276,000	7,412,000	7,960,000	8,576,000	9,273,000	9,786,000	10,470,000
	Deflection δ_L (mm)	33.3	32.8	30.5	28.3	26.5	24.8	23.3
	Deflection δ_d (mm)	156.2	153.0	145.0	138.0	130.0	121.4	111.5
Exterior Girder	Top-Flange	420*29	420*24	380*23	380*19	340*17	320*17	310*16
	(Sectional area cm^2)	(122)	(101)	(87)	(72)	(58)	(54)	(50)
	Web	1500*13	1600*14	1700*14	1800*15	1900*16	2000*17	2100*18
	(Sectional area cm^2)	(195)	(224)	(238)	(270)	(304)	(340)	(378)
	Bottom-Flange	680*45	640*40	660*36	660*33	600*33	580*31	570*28
	(Sectional area cm^2)	(306)	(256)	(238)	(218)	(198)	(180)	(160)
	Sectional area (cm^2)	623	581	563	560	560	574	587
	Is (cm^4)	2,517,000	2,582,000	2,708,000	2,836,000	2,965,000	3,257,000	3,517,000
	Iv (cm^4)	7,320,000	7,479,000	8,023,000	8,608,000	9,206,000	9,851,000	10,462,000
	Deflection δ_L (mm)	37.1	36.5	33.9	31.5	29.4	27.5	25.9
	Deflection δ_d (mm)	159.6	156.3	148.2	141.0	133.1	124.1	114.2
Total sectional area (cm^2)		2416	2267	2201	2193	2212	2262	2318

Table 9 Design Results for L＝40m (with vert. & horiz. stiffs, SM490Y)

	Web Height (mm)	1700	1800	1900	2000	2100	2200	2300
Interior Girder	Top-Flange	410＊24	390＊23	360＊21	340＊20	330＊18	340＊16	340＊14
	(Sectional area cm^2)	(98)	(90)	(76)	(68)	(59)	(54)	(48)
	Web	1800＊9	1800＊9	1900＊10	2000＊10	2100＊11	2200＊11	2300＊12
	(Sectional area cm^2)	(162)	(162)	(190)	(200)	(231)	(242)	(276)
	Bottom-Flange	660＊35	620＊35	630＊32	590＊32	550＊31	520＊33	480＊31
	(Sectional area cm^2)	(231)	(217)	(202)	(189)	(171)	(172)	(149)
	Sectional area (cm^2)	491	469	467	457	461	468	472
	Is (cm^4)	2,561,000	2,716,000	2,831,000	2,977,000	3,145,000	3,415,000	3579000
	Iv (cm^4)	7,729,000	8,274,000	8,900,000	9,450,000	10,000,000	11,028,000	11430000
	Deflection δ_L (mm)	31.3	29.4	27.4	25.8	24.3	22.9	21.5
	Deflection δ_d (mm)	144.0	137.4	130.6	124.3	119.3	112.7	106.1
Exterior Girder	Top-Flange	410 ＊ 26	400 ＊ 24	360 ＊ 23	360 ＊ 21	360 ＊ 17	350 ＊ 15	330 ＊ 14
	(Sectional area cm^2)	(107)	(96)	(83)	(76)	(61)	(53)	(46)
	Web	1800＊9	1800＊9	1900＊10	2000＊10	2100＊11	2200＊11	2300＊12
	(Sectional area cm^2)	(162)	(162)	(190)	(200)	(231)	(242)	(276)
	Bottom-Flange	690＊36	630＊37	620＊35	600＊34	590＊32	560＊31	510＊31
	(Sectional area cm^2)	(248)	(233)	(217)	(204)	(189)	(174)	(158)
	Sectional area (cm^2)	517	491	490	480	481	468	480
	Is (cm^4)	2,733,000	2,877,000	3,021,000	3,191,000	3,293,000	3,388,000	3627000
	Iv (cm^4)	7,815,000	8,369,000	8,974,000	9,566,000	10,212,000	10,693,000	11362000
	Deflection δ_L (mm)	34.9	32.8	30.6	28.7	26.5	25.0	23.6
	Deflection δ_d (mm)	147.1	140.4	133.5	127.0	121.9	115.7	109.0
Total sectional area (cm^2)		2017	1920	1914	1873	1884	1872	1905

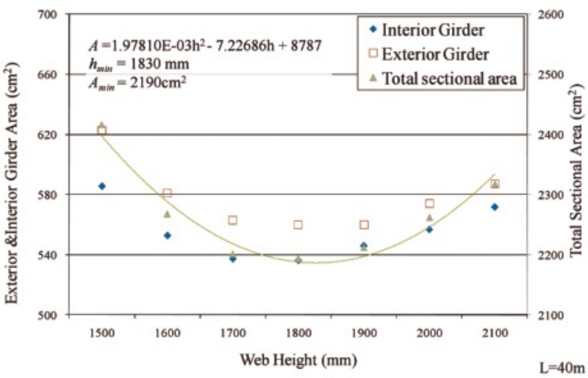

Figure 12 Optimum Girder Height for L＝40m (with vertical stiffener, SM490Y)

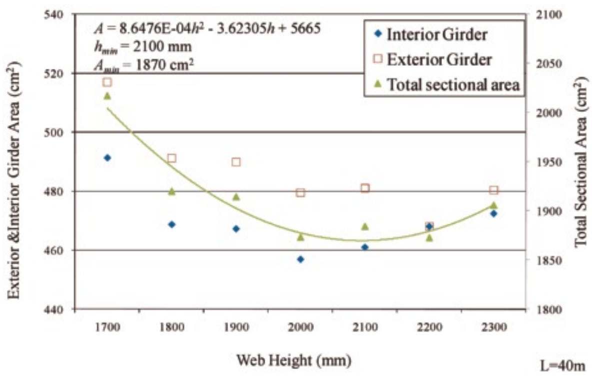

Figure 13 Optimum Girder Height for L＝40m (with vert. & horiz. Stiffs., SM490Y)

6.2 Stiffness and Deflections

Moment of inertia of the external and internal girders for the steel section, I_s, and the composite section, I_v, are plotted in Fig. 14 when the girder height varies. As seen in the previous cases, the moment of inertia is proportional with respect to the girder height. From Fig. 14, it is found that the ratio of the moment of inertia of the composite girder to the steel girder lies in a narrow range from 2.9 to 3.2. This ratio is smaller than the span lengths L＝20m and 30m because the same slab sizes are used in all designs.

The deflections due to the live loads are plotted in Fig. 15 which shows clear inverse proportion to the web height. As similarly to the other span lengths, the deflection limit

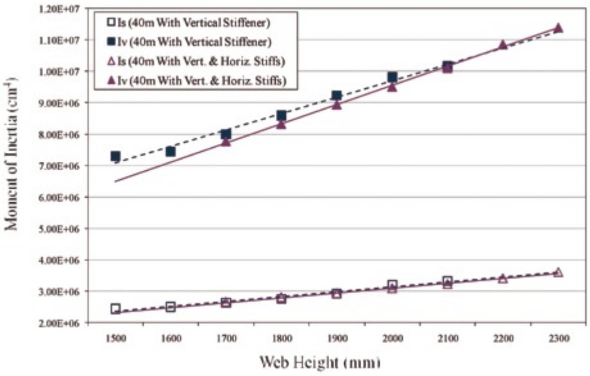

Figure 14 Moment of Inertia, L=40m

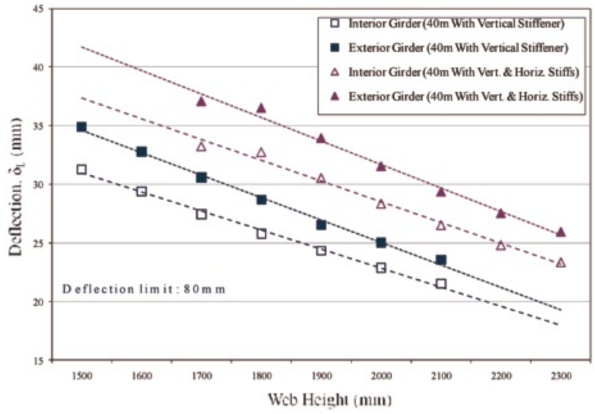

Figure 15 Deflections due to Live Load, L=40m

80mm for live load by JSHB (JRA 2002) for the span length 40m is away above the actual deflections. This implies that the deflection (stiffness) does not control the design.

7. Summary

Based on the studies to investigate the optimum girder height for the benchmark bridges, the results are summarized in Fig. 16 for the span lengths L=20m, 30m and 40m. Note that different strength of material is used for each span length. It can be seen that; (1) the optimum girder height in case of using both vertical and horizontal stiffeners is given by the ratio of girder height to span length h_{min}/L=1/16 to 1/19 depending on the span length; (2) for the case of the web with vertical stiffener but without horizontal stiffener the optimum girder height ratio is h_{min}/L=1/16 to 1/22; and (3) for the case of the web without both vertical and horizontal stiffeners, the optimum girder height ratio is h_{min}/L=1/18 to 1/24. The text books of bridge engineering say the optimum girder height ratio is 1/18 to 1/20 (NAKAI, TOMA and NIWA, 2005) or 1/15 to 1/20 (HAYASHIKAWA 2000).

It is found that the shorter the span length, the larger the ratio of the optimum girder height to the span length. This is because neglecting the stiffeners makes the web thickness large which leads to lower web height to reduce the total sectional area of girders. Lowering the stiffness of girders would not be

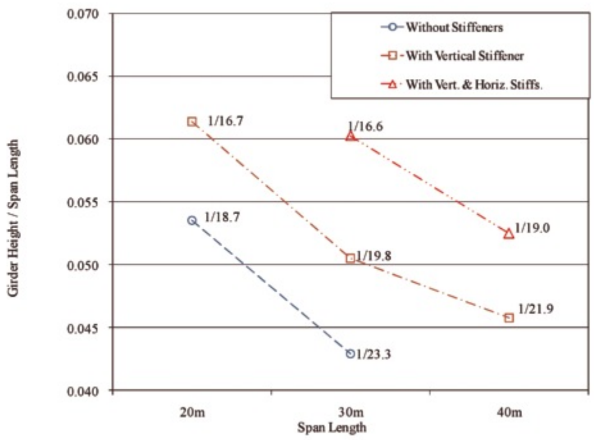

Figure 16 Ratio of Optimum Girder Height to Span Length

a problem to meet the deflection limit.

In general, neglecting of the horizontal stiffener is recommended to reduce the number of steel member components, thus reduce the fabrication cost, for the span lengths in this study, but the vertical stiffener should be used for the span lengths L=30m and 40m. If the vertical stiffener is neglected for large span bridges, the web thickness becomes unrealistically large.

Total sectional areas of the four girders at the optimum girder height are plotted in Fig. 17. It can be seen that when more stiffeners are used the sectional area becomes smaller for the same span length. It should be noted that the section at mid-span is only considered in this study. Therefore, the optimum web depth would be slightly lower if the entire

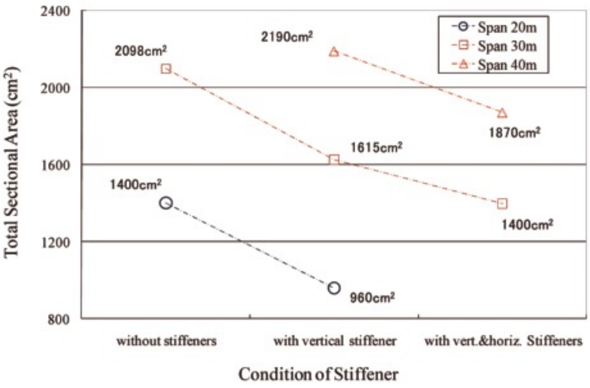

Figure 17 Minimum Sectional Areas with Optimum Girder Height

span length was considered to minimize the total weight instead of considering the sectional area at mid-span only.

Acknowledgement:

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