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Total Cost Optimum of I-Section Girders

Dimensionnement de poutres à section en I en vue d'un coût total optimal

Optimierung von I-Stahlträgern bezüglich der Totalkosten

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1. INTRODUCTION

The optimum design for I-section girders has been investigated considerably, and most of the investigations aim at a minimum-weight-design or a design including only the cost of shop welding in the fabrication cost. Considering all of the fabrication costs, however, the optimum values of design variables will vary remarkably. Therefore, a total cost optimum design, in which an objective function considers material cost as well as fabrication cost including costs of full-scale-drawing, machining, shop welding, shop assembly and shop painting, has to be done. Since such variables as plate thickness, surface area and weight of members, material grade, etc., are included in fabrication costs, the optimum value of the objective function may not be exactly computed, if some of variables are omitted. Therefore, the design variables to be used in this investigation include almost all dimensions of a cross section.

At the present study, a computer-aided, optimum design for single simply supported girders is carried out by SLP method (Sequence of Linear Programming method).[1),2)] If their upper and lower lateral bracings and sway bracing are designed and their dimensions are determined, it is posible to do an automated design by the use of an automated drawing machine.

2. OPTIMUM DESIGN FOR I-SECTION GIRDERS

Material S, cover plate thickness T_c, cover plate width B_c, flange plate thickness T_f, flange plate width B_f, web plate thickness T_w, web plate height B_w, and segment length of a girder section C_ℓ are selected as design variables. Concerning S, steel of $41kg/mm^2$ in tensile strength is expressed with 4, $50kg/mm^2$ is expressed with 5 and $58kg/mm^2$ with 6, and an intermediate value is set on a continuous function.

The constraints contain limit of stress, limit of deflection, limit of plate width to thickness, as specified at the Specifications, limit of flange width to web height, namely $B_f/B_w=1/3\sim1/6$, and upper and lower limits of the values of design variables, which are also used as move limits.

When an allowable tensile stress and an allowable compressive stress of a material are given by σ_{at} and σ_{ac}, respectively, and a ratio of height to thickness of web plate is given by γ, σ_{at}, σ_{ac} and γ are expressed as a function of S as follows:

$$\sigma_{at}=\sigma_{at}(S), \qquad \sigma_{ac}=\sigma_{ac}(S) \qquad \cdots\cdots\cdots\cdots (1)$$

$$\gamma=\gamma(S) \qquad \cdots\cdots\cdots\cdots (2)$$

Then, an objective function Z is expressed with

$$Z=\sum_j \rho\cdot V_j\cdot C\cdot CM+\sum_j\sum_i H_{ij}\cdot SMH+\sum_k\sum_\ell \tilde{H}_{k\ell}\cdot SMH, \qquad \cdots\cdots\cdots\cdots (3)$$

where V_j: volume of the j-th element, ρ: unit weight of steel material, C: coefficient for unit cost of steel material, CM: unit cost of steel material, SMH: unit cost for one man hour work, H_{ij}:work man hour of the i-th manufacturing operation of the j-th element as a function of design variables, $\tilde{H}_{kl}$: work man hour of the k-th manufacturing operation of the l-th element as a fixed value. When, C is considered as a function of T, S and B, and C_1, C_2 and C_3 indicate the case of the function of T, C, the case of the function of S, C and the case of the function of B, C, respectively, the following expressions are obtained:

$$\left.\begin{array}{ll} C_1(T)=0.0348T^2-0.0845T+1.2091 & \\ C_2(S)=0.27S-0.08 & \\ C_3(B)=1.0 & \text{for } B<200(\text{cm}) \\ C_3(B)=1.0+(B-200)/(0.3\ \text{CM})\times 0.01 & \text{for } B\geqq 200(\text{cm}) \end{array}\right\} \cdots\cdots\cdots\cdots (4)$$

where T: plate thickness, B: plate width. H_{ij} can be considered as a function of S, T, W and A_r, where W: weight, A_r: surface area. HA is the coefficient of work man hours depending on S, and the following equation may be obtained:

$$H_{ij}=H_{ij}\times HA(S), \qquad \cdots\cdots\cdots\cdots (5)$$

where

$$HA(S)=0.04S^2-0.29S+1.52. \qquad \cdots\cdots\cdots\cdots (6)$$

The coefficients of Eqs. (4) and (6) are obtained on the basis of actual examples at a bridge fabricating shop in Japan. In the case of welded joints, the work man hours of butt welded joint, H_{ij}, and fillet welded joint, H'_{ij}, become a function of total welded length, but their calculation is to be made with a ratio, η, of equivalent welded length to 6^{mm} fillet. Assumed as a function of T, H_{ij} and H'_{ij} are calculated by the following equations, that is, in the case of butt welds,

$$H_{ij}=H_{ij}(L_1),\ L_1=L_1\times\eta_1(T),\ \eta_1(T)=1.2T^2+3.8T+1.3 \qquad \cdots\cdots\cdots\cdots (7)a$$

and in fillet welds,

$$H'_{ij}=H'_{ij}(L_2),\ L_2=L_2\times\eta_2(T),\ \eta_2(T)=0.0476T^2+0.1952T+0.7572 \qquad \cdots\cdots\cdots\cdots (7)b$$

where L_1, η_1: in the case of butt welds, total equivalent welded length and ratio of equivalent welded length, respectively; L_2, η_2: in the case of fillet welds, the same as L_1, η_1. H_{ij} for marking and painting may be considered a function of A_r.

The procedure of this optimum design is shown by a block flow chart as in Fig.1, in which X shows the variables to be computed by the simplex method and X^0 shows their initial values.

At this study, single main girders without lateral bracings and sway bracing are treated, because omitting of the bracings does not affect the optimum value of total cost.

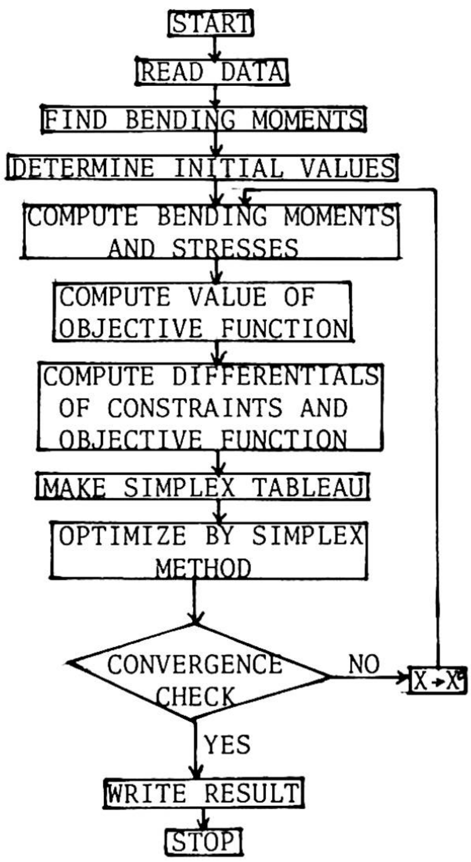

Fig.1. Flow chart of optimum design of girders

3. EXAMPLE OF OPTIMUM DESIGN

3.1 The conditions of design are given as follows:

1) type: I-shaped and deck-type welded railway plate girder, 2) live load: KS18 specified at the Railway Bridge Specifications in Japan, 3) span length: 5 kinds of span length, 16^m, 19^m, 22.3^m, 25.5^m and 30^m, 4) specifications: the Japanese Specifications for Design of Steel Railway Bridges.[3)]

It is assumed that a girder can be provided with three kinds of variation of sections as seen in Fig.2 with NA=2, 3 and 4, in which NA means the number of different girder sections. The upper cover and flange plates are symmetrical with the lower plates.

σ_{at}, σ_{ac} and γ are respectively given at the Specification as:

$$\left.\begin{array}{l} \sigma_{at}=(0.125S^2-0.792S+2.168)\times 1300 \\ \sigma_{ac}=50S^2+50.5S+199-(0.2S^2-1.3S+2.5)\times(\ell/B_f)^2 \end{array}\right\} \cdots\cdots\cdots\cdots (1)a$$

Table 1. Comparison of optimum values for span length of 2230^{cm}

SMH (1000 yen)	NA	S_1	S_2	S_3	T_c (cm)	T_{f1} (cm)	T_{f2} (cm)	T_{f3} (cm)	T_w (cm)	B_c (cm)	B_{f1} (cm)	B_{f2} (cm)	B_{f3} (cm)	B_w (cm)	$SLEG_1$ (cm)	$SLEG_2$ (cm)	$SLEG_3$ (cm)	$SLEG_4$ (cm)
0.0	2	4.0			2.00	1.86			1.19	48.1	44.7			183.8	740.2	1115.0		
1.6	2	4.0			1.83	2.09			1.15	43.9	50.2			178.5	672.5	1115.0		
3.2	2	4.0			1.62	2.33			1.11	38.9	56.0			172.4	589.2	1115.0		
0.0	3	4.0	4.0		1.95	2.00	1.40		1.15	46.8	48.0	29.6		177.8	712.6	1027.2	87.8	
1.6	3	4.0	4.0		1.80	2.29	1.40		1.07	43.2	54.9	27.8		166.5	644.1	1027.2	87.8	
3.2	3	4.0	4.0		1.65	2.35	1.40		1.09	39.7	56.4	28.2		169.3	597.6	1027.2	87.8	
0.0	4	4.0	4.0	4.0	1.58	2.29	1.86	1.40	1.14	38.0	54.9	44.7	29.5	177.2	583.0	766.3	150.0	199.1
1.6	4	4.0	4.0	4.0	1.45	2.41	1.83	1.40	1.12	34.9	57.9	44.0	29.0	173.7	533.3	788.9	137.8	188.3
3.2	4	4.0	4.0	4.0	1.30	2.68	1.82	1.40	1.11	31.2	57.3	43.6	28.6	171.8	472.7	800.4	132.3	182.3

SMH (1000 yen)	NA	δ_1 (cm)	δ_2 (cm)	Z (1000 yen)	Weight (ton)	β	σ_{a1} (Kg/cm²)	σ_1 (Kg/cm²)	σ_{a2} (Kg/cm²)	σ_2 (Kg/cm²)	σ_{a3} (Kg/cm²)	σ_3 (Kg/cm²)	σ_{a4} (Kg/cm²)	σ_4 (Kg/cm²)	α	$\frac{SLEG_1}{0.5L}$	$\frac{SLEG_2}{0.5L}$	$\frac{SLEG_3}{0.5L}$
0.0	2	2.21	1.85	288.3	4.92	1.01	1155	1155	1166	1166					12.1	0.664		
1.6	2	2.30	1.93	555.6	4.91	0.97	1170	1170	1174	1174					12.5	0.603		
3.2	2	2.40	2.01	804.9	4.95	0.93	1184	1184	1179	1179					12.9	0.528		
0.0	3	2.30	1.92	284.1	4.83	0.96	1165	1165	1171	1171	1122	517			12.5	0.639	0.921	
1.6	3	2.48	2.08	571.5	4.83	0.88	1182	1182	1178	1178	1111	607			13.4	0.578	0.921	
3.2	3	2.45	2.05	841.0	4.83	0.90	1185	1185	1179	1179	1114	583			13.2	0.536	0.921	
0.0	4	2.34	1.96	270.1	4.58	0.96	1182	1182	1178	1178	1166	1166	1122	1122	12.6	0.523	0.687	0.134
1.6	4	2.40	2.01	578.2	4.57	0.94	1188	1188	1180	1180	1165	1165	1119	1119	12.8	0.478	0.708	0.124
3.2	4	2.42	2.03	873.7	4.58	0.92	1186	1186	1180	1180	1165	1165	1117	1117	13.0	0.424	0.718	0.119

$\gamma=2.5S^2-47.5S+305$ ··(2)a

where ℓ represents a distance between fixed points of a flange plate. If α is assumed to be a value of a span length divided by a web height, the initial values of B_w, B_c, T_c, B_f and T_f are calculated under the assumption of α, but the initial values of S and locations of joint are given as constant values independently of α. Now, the calculation of the initial values by a computer, makes it possible to do an automated design.

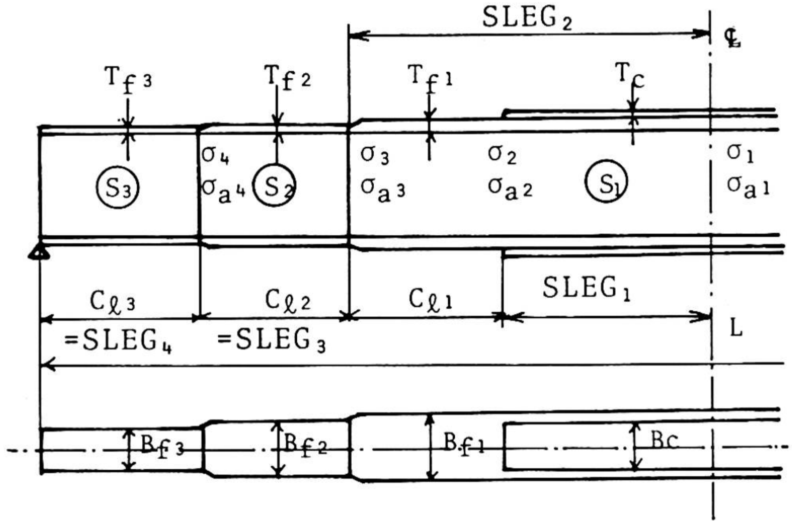

Fig.2. Notations for deck plate girder

3.2 Results of Calculation

As an example of the results of calculation, the case of span length of 22.3^m are summarized in Table 1, in which SLEG: values shown in Fig.1, δ_1:deflections due to live load and dead load at the span center, δ_2: deflections due to live load at the span center, Z: values of objective function, β: coefficients to be given later.

3.3 Discussion

As the result, the followings are discussed:

(1) The materials were considered as the design variables too, but the calculation shows that the case of S=4, namely SS41 steel will give optimum values.

(2) In the case of material cost only, the value of an objective function becomes the cheaper, with an increase of the number of different sections. On the other hand, in the case of material cost and fabrication cost, the value of the objective function becomes the higher and the girder weight becomes the lighter, with an increase of the number of different sections.

(3) Conventionally a web height B_w used to be expressed in terms of the following relation:

$$B_w=\beta\sqrt{\frac{M}{\sigma\cdot T_w}} \qquad \cdots\cdots\cdots\cdots(8)$$

where β: coefficient, M: bending moment. The values of β,calculated by the optimum values, are shown in Table 2. They do not change greatly as to span lengths, but generally become the larger , the longer the span length is.

Table 2. Values of coefficient β

SMH	NA \ L	1600^{cm}	1900^{cm}	2230^{cm}	2550^{cm}	3000^{cm}
	2	0.96	0.97	1.01	1.02	1.00
0.0	3	0.93	0.94	0.96	0.99	1.00
	4	0.92	0.94	0.96	0.98	1.03
	2	0.92	0.94	0.97	0.97	1.01
1.6	3	0.89	0.88	0.88	0.91	1.01
	4	0.89	0.93	0.94	0.93	1.04
	2	0.92	0.93	0.93	0.95	1.02
3.2	3	0.89	0.90	0.90	0.90	1.03
	4	0.87	0.89	0.92	0.94	1.05

(4) The values of SLEG/0.5L are shown in Table 3, where L: span length. In the table, $SLEG_1$ is the shorter, the higher SMH is, while flange plate lengths do not change greatly.

Table 3. Values of SLEG/0.5L

SMH	NA	SLEG \ L	1600^{cm}	1900^{cm}	2230^{cm}	2550^{cm}	3000^{cm}
0.0	2	$SLEG_1$	0.651	0.661	0.664	0.671	0.681
	3	$SLEG_1$	0.625	0.631	0.639	0.645	0.658
	3	$SLEG_2$	0.921	0.921	0.921	0.921	0.921
	4	$SLEG_1$	0.492	0.505	0.523	0.539	0.558
	4	$SLEG_2$	0.668	0.679	0.687	0.696	0.698
	4	$SLEG_3$	0.140	0.140	0.134	0.131	0.117
1.6	2	$SLEG_1$	0.554	0.582	0.603	0.619	0.641
	3	$SLEG_1$	0.537	0.565	0.578	0.594	0.611
	3	$SLEG_2$	0.921	0.921	0.921	0.921	0.921
	4	$SLEG_1$	0.447	0.455	0.478	0.492	0.489
	4	$SLEG_2$	0.700	0.698	0.708	0.715	0.693
	4	$SLEG_3$	0.115	0.124	0.124	0.128	0.118
3.2	2	$SLEG_1$	0.492	0.489	0.528	0.558	0.588
	3	$SLEG_1$	0.485	0.506	0.534	0.548	0.556
	3	$SLEG_2$	0.921	0.921	0.921	0.921	0.921
	4	$SLEG_1$	0.356	0.373	0.424	0.440	0.396
	4	$SLEG_2$	0.694	0.717	0.717	0.707	0.673
	4	$SLEG_3$	0.148	0.138	0.120	0.131	0.143

(5) Except for the value of σ_3 in NA=3, the other maximum working stresses reach up to the full allowable stresses. σ_3 does not become fully-stressed, because the flange plate at this position is determined by its minimum thickness 1.4^{cm} and by its width calculated at $B_f \geqq B_w/6$.
(6) T_c and B_c are the smaller, the higher the fabrication cost is. On the other hand, T_{f1} and B_{f1} are the larger, the higher the fabrication cost is. There is no remarkable difference due to the difference of fabrication cost at the dimension of flange section at the other positions.
(7) The leg length at fillet welds is the smaller and the fabrication cost is the cheaper, the wider the flange plate is and the thinner the flange plate is.
(8) At the present example of design, the optimum dimensions of section for 5-kinds of the span length are calculated, but they can be calculated for the other span lengths by the following procedure. B_w is calculated from Eq. (8) by assuming σ and T_w, and using M and β. Then, the position of joint is obtained from Table 3, and except T_{f2} and B_{f2} in NA=3, the dimension of girder section at the span center and all of the positions of joint can be found by the fully stressed design. However, in NA=3, $T_{f2}=1.4^{cm}$ and $B_{f2}=B_w/6$ or $B_{f2} \geqq 24^{cm}$ are applied.
(9) As seen in the value of β, for the case of material cost only the optimum girder height varies, but for variable unit fabrication costs it does not greatly vary.

4. CONCLUSION

It is indicated that it is possible to carry out the optimum design considering material cost and total shop fabrication cost by means of a program for computer design which is presented at the present study, and it will be possible to extend this program to the computation for a girder with different upper flange section from lower flange section, a composite girder and a continuous girder; and a part of this program has been completed already.

At the present program, transportation and erection costs depending on site conditions are omitted, but in the future, in the case of a specific or individual bridge, it would be necessary to investigate on an overall cost optimum design containing the transportation and erection costs.

REFERENCES

1) T. Cho "Optimum Design for Structures", Asakura, Tokyo, 1971, pp. 29-41 (in Japanese).
2) Y. Ochi, "Tecnique of Computer Analysis and Its Application", Morikita, Tokyo, 1970, pp. 155-164 (in Japanese).
3) Japan Society of Civil Engineers, "The Specifications for Design of Steel Railway Bridges", 1974, (in Japanese).

SUMMARY

A program of optimum design considering material cost and total shop fabrication cost for the most foundamental I-section girders of steel bridges is presented with design examples. The influence of 16 design variables on the total cost is discussed, to improve the computer-aided automated optimum design.

RESUME

Un programme de dimensionnement optimal tenant compte du coût des matières et des coûts de fabrication est appliqué aux plus élémentaires sections en I des poutres de pont métallique. Des exemples sont donnés. L'influence de 16 variables de dimensionnement sur les coûts totaux est étudié afin d'améliorer le dimensionnement optimal à l'ordinateur.

ZUSAMMENFASSUNG

Es wird ein Programm für die Optimierung von I-Stahlträgern mit Rücksicht auf Material- und Herstellungskosten präsentiert und dessen Anwendung an Beispielen dargelegt. Der Einfluss von 16 Entwurfsvariablen auf die Totalkosten wird untersucht, um die computerunterstützte Entwurfsoptimierung zu verbessern.