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Optimum Design of Cable-Stayed Bridges using an Optimality Parameter

Calcul de ponts haubannés à l'aide d'un paramètre d'optimisation

Die Berechnung von Schrägseilbrücken mit einem Optimierungsparameter

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1. INTRODUCTION

The optimization discussed in this paper is applied for the design of the overall super-structure of cable-stayed bridges. Then the hierarchy of this study is belonged to category 3 described in the introductory report of the 10th congress by Templeman(1). The optimization method developed here is a kind of the optimality criterion method discussed by Templeman, Gellatly and Dupree(1)(2).

Up to the present many nonlinear programming techniques have been developed and applied for the optimum design of bridge super-structures, but successful applications are very few. Because the fully stressed design for a common type of super-structure such as girder bridge is a convenient design method and gives the satisfactory economical result. Therefore from the practical point of view, the optimum design without considering the price of sub-structure may be important for only some specific type of bridges such as cable-stayed bridges, suspension bridges.

In this study, an optimality condition parameter is obtained by a mean of the numerical calculation and the parameter is used to determine the economically proportional sizes of the cable and girder.

2. PRECONDITIONS FOR THE NUMERICAL PROCEDURE

To determine an optimality parameter by numerical process, the following preconditions must be given.

(1) Utilization of the structural nature of cable-stayed bridges is very important to find out the optimality condition. Fig. 1, 2 show the static behavior of cable-stayed bridges due to dead loads and live loads. These examples show that the each rigidity value of cable and girder is not main factor of changing the section force distribution. It is obvious that the main influence to the girder section force is a rigidity ratio, $\gamma = EG \cdot IG / EC \cdot AC$. where, EG is the modulus of elasticity of girder, IG is the moment of inertia of girder, EC is the modulus of elasticity of cable, AC is the cable area.

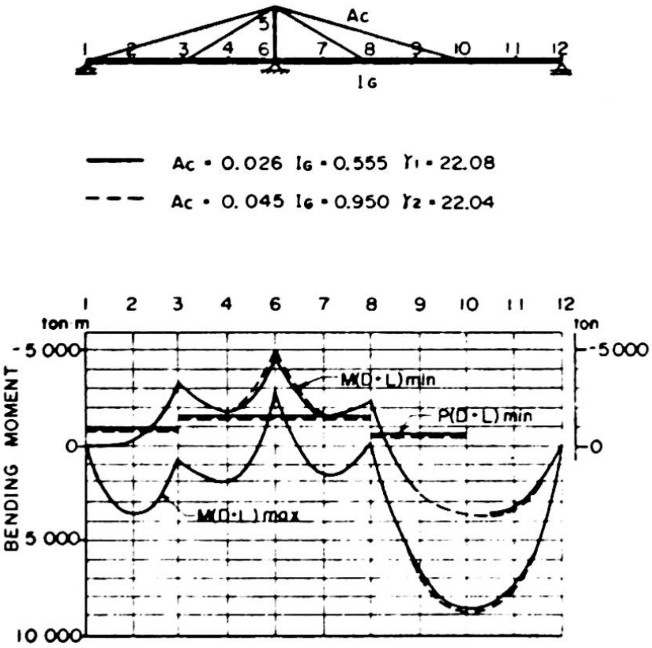


Fig. 1 2 Span Bridge

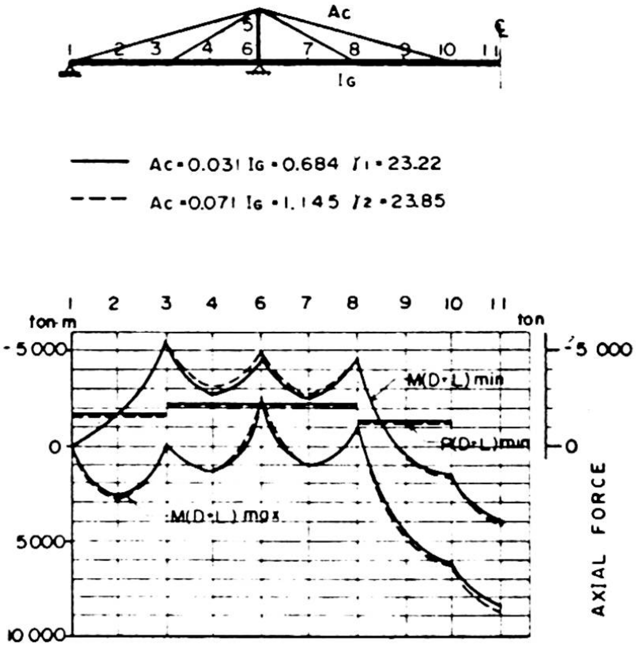


Fig. 2 3 Span Bridge

(2) The price ratio of materials including the cost of fabrication and erection is assumed as follow.

structural steel : high tensile steel : cable = 1 : 1.15 : 2.0

(3) Fig. 3 is the analyzing structural system which rigidity ratio is assumed as:

$\gamma_{try} = EGX_1/ECX_2$ X_1: moment of inertia of girder
X_2: cable area

Fig. 4 is the actual redesign structure which rigidity ratio is expressed by:

$$\gamma_{real} = \frac{EG/NG \cdot \sum_{n=1}^{NG} IGn}{EC/NC \cdot \sum_{n=1}^{NG} ACn}$$

IGn: moment of inertia of girder
ACn: cable area
NC, NG: number of cable and girder

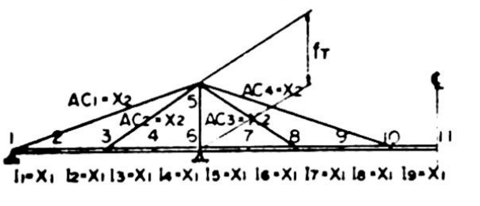


Fig. 3 Assuming Member System

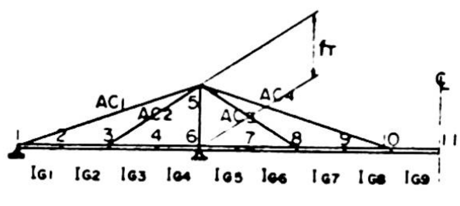


Fig. 4 Actual Member System

The approximate design process must be carried out by keeping the following ctiteria.

$$0.9 < \gamma_{try}/\gamma_{real} < 1.1$$

(4) The section and material compositions of stiffening girder are illustrated in Fig. 5, 6. The price of girder member is determined by the element design based on the fully stressed design.

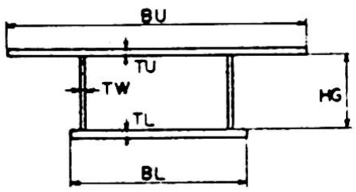


Fig. 5 Girder Section

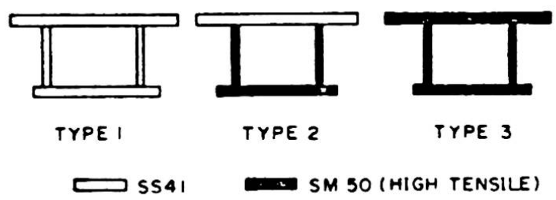


Fig. 6 Material Composition of Girder

3. DETERMINATION OF AN OPTIMALITY PARAMETER

An optimality parameter is determined after carried out the next 2 step procedure.

(1) Characteristic Parameter (Step 1)

The basic structure to be effectively prestressed is determined by the grid search procedure, because two design variables are employed for the global system optimization. The cost evaluation is made by the following equation.

$$Z(X_1,X_2) = \sum_{m=1}^{NG} \text{price } G(X_1,X_2) + \sum_{n=1}^{NC} \text{price } C(X_1,X_2)$$

X_1: moment of inertia of stiffening girder
X_2: cable area
price G: price evaluation of girder depend on X_1, X_2
price C: price evaluation of cable depend on X_1, X_2

The characteristic parameter at the grid point is expressed as:

$$KE = EG \cdot IG / EC \cdot AC \cdot HG^2$$

IG: moment of inertia of stiffening girder
AC: cable area
HG: web depth

(2) Determination of an Optimality Parameter (Step 2)

Prestressing forces (external loads) are introduced into the cable of basic structural system determined by above procedure. In this step, prestressing forces are design variables (Fig. 7). In case of two design variables, an optimality parameter minimizing the total cost is also selected among the grid points number of characteristic parameters, and it is expressed by the following nondimensional parameter.

$$KOPT = EG \cdot IGOPT / EC \cdot ACOPT \cdot HGOPT^2$$

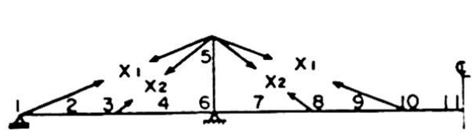


Fig. 7 Prestressing System

4. NUMERICAL MODELS AND RESULTS

Numerical calculation is carried out for nine cases of analyzing models. Structural models of 2-span and 3-span bridges are illustrated in Fig. 8, 9.

The differences of analyzing models are indicated belows.

2-span Bridge

Case	Tower Height	Web Thick	Steel Weight	Other
1	30 m	10 mm	3.3 t/m	
2	30 m	14 mm	3.3 t/m	
3	30 m	10 mm	3.3 t/m	Knie Type
4	30 m	10 mm	5.3 t/m	
5	35 m	10 mm	3.3 t/m	
6	40 m	10 mm	3.3 t/m	

3-span Bridge

Case	Tower Height	Web Thick	KE
7	30 m	10 mm	2.58
8	30 m	14 mm	2.64
9	30 m	14 mm	2.96

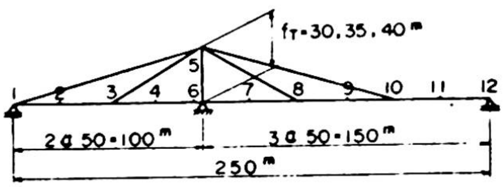


Fig. 8 2 Span Model

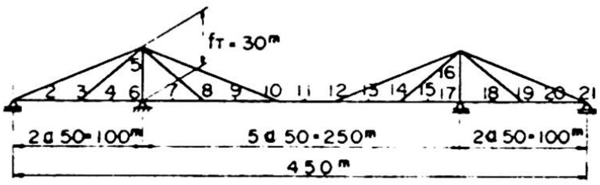


Fig. 9 3 Span Model

Table 1 Numerical Result of Parameters

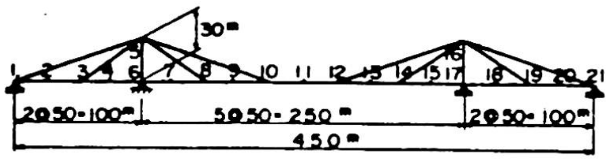
	CASE	DESIGN STEP	KE PARAMETER	KOPT	PARAMETER
2 SPAN	1	A FULLY STRESS	4.0 ~ 5.0	2.55	2.48
		B BASIC STRUCTURE	0.92 ~ 7.56		
		C PS. ARRANGEMENT	2.47 ~ 2.89		
	2	B BASIC STRUCTURE	0.96 ~ 7.88	2.49	
		C PS. ARRANGEMENT	2.54 ~ 2.96		
	3	B BASIC STRUCTURE	0.92 ~ 7.73	2.43	
		C PS. ARRANGEMENT	2.43 ~ 2.90		
	4	B BASIC STRUCTURE	0.92 ~ 7.03	2.55	
		C PS. ARRANGEMENT	2.53 ~ 2.89		
	5	B BASIC STRUCTURE	0.92 ~ 7.05	2.45	
		C PS. ARRANGEMENT	2.41 ~ 2.89		
	6	B BASIC STRUCTURE	0.92 ~ 7.50	2.41	
		C PS. ARRANGEMENT	2.41 ~ 2.89		
3 SPAN	7	A FULLY STRESS	3.22 ~ 4.73	2.58	2.46
		B BASIC STRUCTURE	0.92 ~ 5.67		
		C PS. ARRANGEMENT	2.14 ~ 2.58		
	8	B BASIC STRUCTURE	0.96 ~ 5.81	2.27	
		C PS. ARRANGEMENT	2.25 ~ 2.65		
	9	B BASIC STRUCTURE	0.96 ~ 5.81	2.53	
		C PS. ARRANGEMENT	2.53 ~ 2.96		
TOYOSATO BR.		SPAN 80.5 · 216 · 80.5 (PWS)			2.87
SUEHIRO BR.		SPAN 109 · 250 · 109 (PWS)			2.89
ONOMICHI BR.		SPAN 85 · 215 · 85 (LOCKED-COIL)			2.39

Numerical results of characteristic parameter and optimality parameter are listed in Table 1. The KE parameter of the cable-girder system determined by the fully stressed design is in the small range (3.∿ 5.). On the other hand the KE parameter determined by the approximate design process developed in this study is in the fairly large range (1.∿8.). Prestressing forces are introduced into the suitable basic structure which cable components are not fully stressed. From the results of case 7 ∿ case 9, it is obvious that KE value reduces about 15 percents by introducing the prestressing forces.

5. AN EXAMPLE OF THE DESIGN USING AN OPTIMALITY PARAMETER

The main difference of this method from the usual design method is the use of the parameter KOPT = 2.5 obtained by numerical calculation as shown in Fig. 10.

dead load .... 10.0 t/m
line load .... 50.0 t
uniform load .... 3.5 t
impact 0.2
optimality
  parameter...... KOPT=2.5
assuming rigidity
  girder .... IG=1.0 m^4
  cable .... AC=0.046



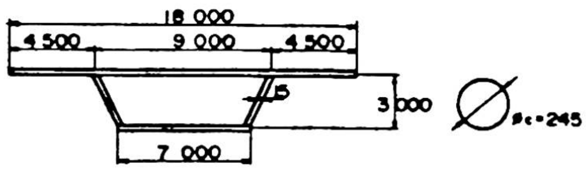


Fig. 10.
Design Conditions
and Basic Dimensions

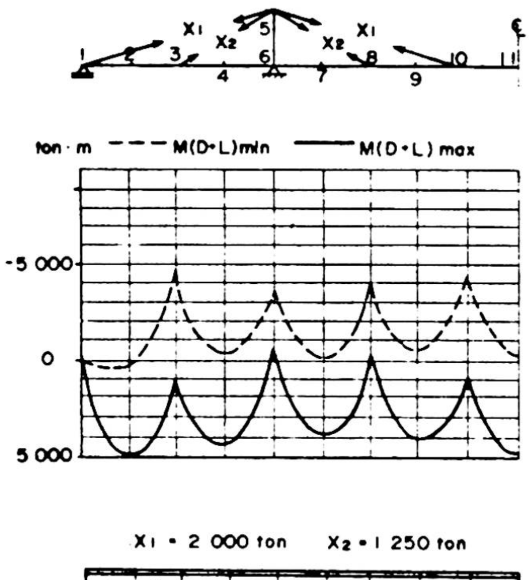
The optimum bending moment arranged by prestressing forces and the moment inertia of girder members are also illustrated in Fig. 11.

By using the optimality parameter, structural designer can get the reasonable sections of girder and prestressing forces of cable-stayed bridges by one time trial. The assuming rigidity of analyzing system determined by using an optimality parameter is very close to the real rigidity of the final structure.

6. CONCLUSION

Unexperienced structural engineer may feels some difficulties to design the economical cable-stayed bridge. Because allowable stress guarantee the safety of structures, but it does not always guarantee the economical condition. The prices and strength of the cable and steel girder are extremely different. Furthermore the arrangement of the bending stress of the stiffening girder causes the more complicated problem. Therefore the economical criterion for cable-stayed bridges may be important as same as the factor of safety.

Finally the conclusions of the basic study for the optimality criterion method are outlined by the next statements.



In (m^4)	1	2	3	4	5	6	7	8	9
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9
	0.917	1.029	0.917	1.029	1.029	0.917	0.917	0.946	0.917

Fig. 11. Optimum Design

(1) The optimality parameter value of the radial type of the cable-stayed bridge based on the price ratio (structural steel : cable = 1 : 2) exists in the range of 2.0 ∿ 3.0.

(2) The moment of inertia of stiffening girder can be considered as uniform along the girder axis by effectively prestressed.

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SUMMARY

A convenient optimization method using an optimality parameter has been discussed. The optimality parameter is based on the structural nature and the approximate design procedure. This parameter is used to determine the optimum rigidity ratio of the cable-girder system after introducing the prestressing forces. The optimum design using an optimality parameter will be easily accepted by structural engineers as the economical criterion.

RESUME

Une méthode pratique d'optimisation à l'aide d'un paramètre d'optimisation est présentée. Le paramètre d'optimisation est obtenu à partir du caractère structural et de la méthode approximative de calcul. Ce paramètre est employé pour déterminer la rigidité la plus favorable du câble et de la poutre après avoir introduit les forces de précontrainte. Le calcul à l'aide d'un paramètre d'optimisation sera accepté par les ingénieurs comme un critère économique.

ZUSAMMENFASSUNG

Eine anwendbare Optimierungsmethode mit einem Optimierungsparameter wird dargestellt. Der Optimierungsparameter wird aufgrund des Tragwerkssystems und der Näherungsberechnungsmethode bestimmt. Mit diesem Parameter werden die günstigsten Seil- und Trägersteifigkeiten unter Berücksichtigung der Vorspannkräfte bestimmt. Die Berechnung mit einem Optimierungsparameter wird von den Ingenieuren zur Steigerung der Wirtschaftlichkeit angenommen werden.