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Method for Evaluating the Load Carrying Capacity of Existing Bridges
Méthode d'evalution de la capacité portante des ponts
Eine Methode zur Tragfähigkeitsbewertung bestehender Brücken

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SUMMARY
On the basis of inspection, testing and analysis for a number of existing bridges, the factors which have influence on the load carrying capacity of existing reinforced concrete bridges are identified and a finite element model for evaluating the load capacity is developed. A simulation method for the evaluation is proposed, by which the load testing of bridges can be simulated by means of computers and the characteristics of the load carrying capacity of existing bridges can be calculated.

RÉSUMÉ
Sur la base d'inspections, d'essais et d'analyses d'un grand nombre de ponts, les facteurs qui influencent la capacité portante des ponts en béton armé ont été identifiés et un modèle par éléments finis a été développé. Une méthode de simulation pour l'évalution est présentée, par laquelle l'essai de charge du pont peut être simulé au moyen de l'ordinateur; les caractéristiques de la capacité portante des ponts peuvent être ainsi également calculées.

ZUSAMMENFASSUNG
Auf Grund der Untersuchungen, Proben und Analysen von zahlreichen bestehenden Brücken werden die Hauptfaktoren, die Einfluss auf die Tragfähigkeiten von bestehenden Stahlbetonbrücken ausüben, festgestellt und ein Finite-Elemente- Modell für die Tragfähigkeitsbewertung entwickelt. Mittels dieser Methode kann die Belastungsprobe der Brücken mit Hilfe von Computern simuliert und dadurch können die Kennziffern der Tragfähigkeit von Brücken berechnet werden.

1. INTRODUCTION

With the development of transportation, the load carrying Capacity of a number of existing bridges are found to be insufficient due to progressing deterioration and increased loads. There are nearly 136,000 highway bridges in China, About 5,000 of these are judged to be functionally obsolete or inadequate for current requirements, the service age of these bridges are ranged from 30—years to 40—years. In addition, some of bridges constructed over the last 20 years are considered to be structurally deficient because of deterioration or distress[1][2].

While replacing all the deficient bridges mentioned above with new bridges is often extremely difficult and expensive, a moderate increase of structural capacity through rehabilitation and repair is fairly cheap and easy to obtain. To avoid high costs of rehabilitation and repair, the evaluation of the bridges must accuratelly reveal the present load carrying capacity and any further changes in the capacity in the applicable time span. In recent years, many method for evaluating the load carrying capacity of existing bridges have been developed. these method can be roughly divided into three kind: Knowledge—based method; computalional method; and load testing method. The knowledge—based method has the advantage of assessing the damage state of the bridges, but can not give exact index about the load carrying capacity. Most computational methods are similar to design methods, the hypothesis on which design methods based are not quite the same as practical behavior of existing bridges, and computational results may be doubtful. load testing on bridges can directly examine the load capacity and the results are more reliable than other methods. However, it would be very expensive to test all the deficient bridges. In order to explore the load carrying capacity of existing bridges, it is necessary to develop an inexpensive evaluation method which can fully take into account the real behavior of existing bridges and give reliable results about the load capacity.

The objective of this paper is to identify the factors which affect the load carrying capacity of the bridges and develop a simulation method for the evaluation. Using the method, the load testing of the bridges can be simulated by means pf computers and the index about the load carrying capacity can be caculated. An example of evaluating a T-beam bridge is also presented.

2. FACTORS AFFACTING THE LOAD CAPACITY OF R. C. BRIDGES

Over the years of servicing, various forms of deterioration would appear on beams, piers and bases of bridges and all affect the load carrying capacity. So the load carrying capacity include the capacity of upper structure which composed of beams and deck and that of lower structure constituted by piers and bases. Only the upper structural capacity is studied in this paper.

In order to assesss the damage state of old bridges and identify the factors which affect the load carrying capacity of the bridges, a thorough field survey of old R. C. bridges located in Guangdong province in China was made and static and dynamic load tests were performed on some of these bridges[3]. Inspection and testing show that the deterioration emerged on beams and deck are main factors which influence the load carrying capacity. The deficiencies on the attachment such as discharge orifices and expansion joints results in the damages on beams and deck, then have indirect influence on load capacity. Various types of deterioration -efflorescence, leakage, cracking and spalling-can contribute to the reduction of bridge's load capacity to different degree. Ignoring the deficiencies which have little influence on the load capacity and only beams and deck are considered, main factors affecting the R. C. bridge's load capacity can be identified as shown in Fig. 1.

Among the factors, cracking of concrete is very important to estimate the load capacity. The density, width, length and pattern of cracks are significant indexes for the estimation. The factors given in Fig. 1 must be take fully into account in the computational model for evaluation of R. C. bridge's load carrying capacity.

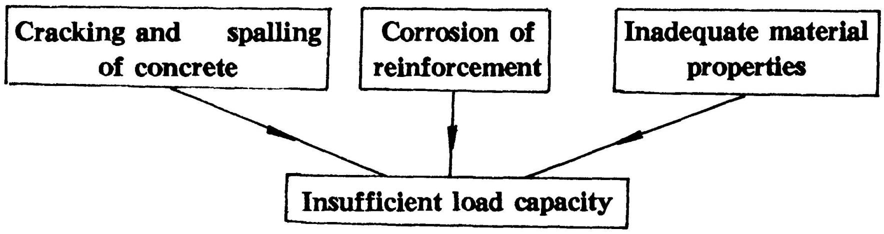


Fig. 1 Main factors affecting load capacity

3. COMPUTATIONAL MODEL FOR R. C. BRIDGE' S LOAD CAPACITY

3. 1 Mathematical Model

Theoretically, for a given loadings and structure type, a bridge' s load carrying capacity can be determinated in terms of the parameters such as load components, dimensions, strength of materials, etc. The evaluation philosophy of an existing bridge must differ from the design philosphy of a new bridge. In this study, the load carrying capacity index, R , is defined as follows:

$$R = g[s(t), f(t), x(t), \varphi(t)] \tag{1}$$

where $S(t)$ represents load effect; $f(t)$ represent strength of materials; $x(t)$ represent dimensions; $\varphi(t)$ is structural integrity and is equal to $(1 - d)$, in which d is damage. All of these parameters are functions of service time t . Assuming that, R is differentiable continuous function of all the parameters, the change of load capacity, $\triangle R$, can be derived from Eq. (1) as:

$$\triangle R = (\partial g/\partial s)\triangle s + (\partial g/\partial f)\triangle f + (\partial g/\partial x)\triangle x + (\partial g/\partial \varphi)\triangle \varphi \tag{2}$$

in which $\triangle s$, $\triangle f$, $\triangle x$ and $\triangle \varphi$ denote the changes of load effect, strength of materials, dimensions and structural integrity, respectively. Over the years of performance, the actual load carrying capacity, R_t , at the time of evaluating, t , is witten as:

$$R_t = R - \triangle R \tag{3}$$

The resistance coefficient, k , can be defined as:

$$K = (R_t - G)/S \tag{4}$$

where G represents dead load effect; S represent the effect of the live loads used for evaluation.

3. 2 Finite Element Model

To reveal the real load carrying capacity of bridges, a rational computational model must be established. Actual behavior and the factors affecting the load capacity must be fully considered in the model. The finite element method is appropriate for dealing with non — homogeneous materials, nonlinear constitutive relationships and complicated boundary conditions. It is easy to dispose deterioration or distress which contributes to reduction of the load capacity by using the finite element method. Thus a finite element model can be developed to caculate the load carrying capacity index, *R* . The major factors in Fig. 1 can be taken into account in the finite element model and constitutive relationships(Fig. 2)

Fig. 3(a)shows a damaged simply supported T—beam, which has four cracks located at A, B, C,and D, respectively. Spalling occurs at location E, and result in corrosion of parts of reinforcing bars. Meanwhile, expansion bearing lose its efficacy. Finite element model of the beam is illustrated in Fig. 3. (b). Details of the model will be described in the following.

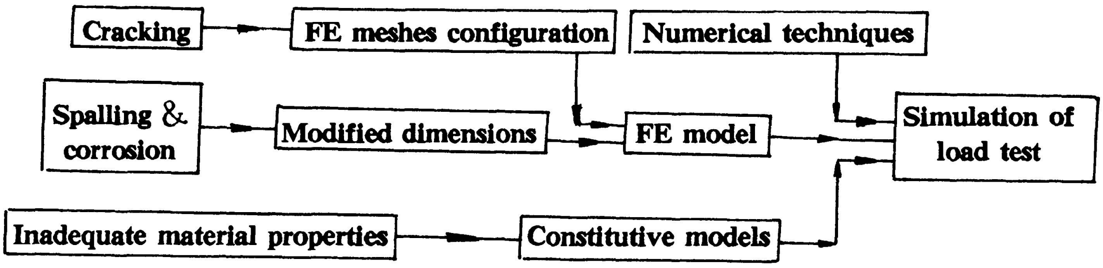


Fig. 2 Management of the factors affecting load capcity

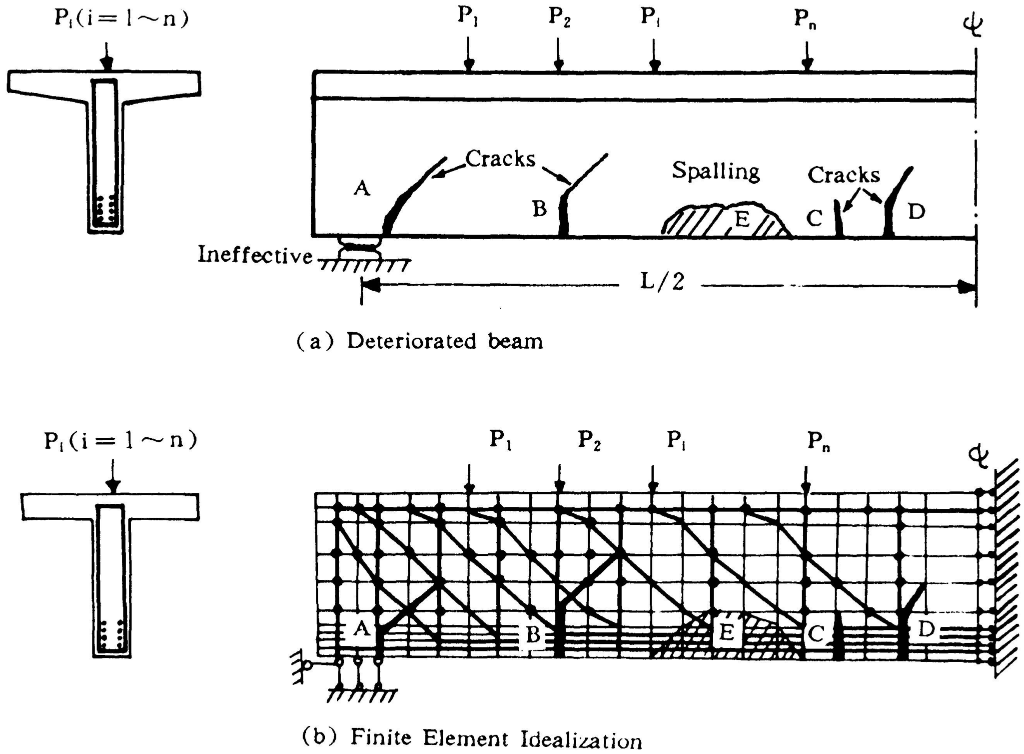


Fig. 3 Finite element model of deteriorated beam

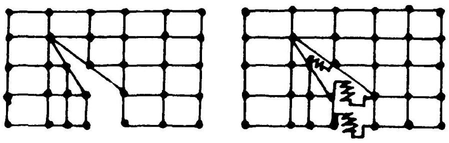
3. 2. 1 Concrete

The assumption of the plane stress is considered to be reasonable for T—beam subject to loadings in—web plane. Reduction of concrete section due to spalling is taken into account by the modified element thickness, T_c , defined as:

$$T_c = K_c T \tag{5}$$

where K_c is modification coefficient, T is original thickness.

Existing cracks are modelled with two techniques: Discrete model and smeared crack model. The discrete model approaches a single fully separative crack by disconnecting nodal points (Fig. 4(a)). Interlock elements are placed across the incompletely separative cracks to simulate aggragate interlock (Fig. 4(b))



(a) (b)

Fig. 4 Discrete crack model

The smeared crack model represent overall influence of many discrete cracks existing in the domain of the element. the constitutive eqation is expressed by[8]:

$$\begin{bmatrix} d\sigma_1 \\ d\sigma_1 \\ d\sigma_1 \end{bmatrix} = \begin{bmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & G_{cr} \end{bmatrix} \begin{bmatrix} d\varepsilon_1 \\ d\varepsilon_2 \\ d\gamma_{12} \end{bmatrix} \tag{6}$$

where G_{cr} is reduced shear modulus which reflects the density, width and degree of separation of the cracks.

3. 2. 2 Steel reinforcement

Main reinforcing bars are represented by axial force elements with two translational degrees of freesom defined at each node. Corrosion of rebars is considered by reduction of the cross sectionl area of the bars. Secondary reinforcement, such as stirrups is assumed to be distributed over concrete elements and forms composite concrete—steel element. The material stiffness of the element is defined as follows [8]:

$$[D] = [D^c] + \sum_{i=1}^{n} [D_i^s] \tag{7}$$

where $[D^c]$ and $[D_i^s]$ are the concrete and reinforcement material stiffness matrices, respectively.

3. 2. 3 Bond between steel reinforcement and concrete

If the influence of bond slip is considered, linkage elements must be set up to model bond behavior, so the number of nodal points will increase greatly. For the sake of utilizing memory capacity of computer effectively, reinforcement may be assumed to be connected directly to the concrete at the nodal points.

4. CONSTITUTIVE RELATIONS FOR THE CONSTITUENT MATERIALS

Material properties have a significant influence on the load capacity. Actual material parameters must be used in constitutive relations. Biaxial nonlinear constitutive relations and failure theories should be applied to explore the realistic load capacity of existing bridges.

The concrete constitutive model and failure crireria of Balakrishnan & Murray[5] are introduced in this study. The model divides the uniaxial response curve for concrete into five damage regions described as linear elastic; compressive strain hardening; compressive strain softening; tensile strain softening; and tensile stiffening regions. When used under biaxial stress conditions, the model is considered orthotropic after cracking. The effect of biaxial stress conditions on peak strength is represented by a variation of the Kupfer—Hilsdorf failure curve in stress space in which the compressive and tensile envelopes are separatelly specified[4][5]. In the tension—compression region, tensile stress less than 0. 5 f_t does not reduce compressive strength. If $\sigma_1 > 0.5f'_t$, the ultimate strength may be described as:

$$f_{tu} = 2f'_c/(1/2 + 2f'_c/f'_t) \tag{8}$$

$$f_{cu} = (-1.5 + f_{tu}/f'_t)\,|f'_c| \tag{9}$$

In compression—compression region, the ultimate compressive strength may be written as:

$$f_{cu} = (1 + 3.65)f'_c/(1 + \alpha)^2 \tag{10}$$

in which $\alpha = \sigma_1/\sigma_2$, σ_1 and σ_2 are major and minor principal stresses respectively, f_{cu} and f_{tu} are peak compressive and tensile stresses respectively. Details of the model are described in reference[5]. The paramefers in the model such as cylinder compressive strength f'_c, elastic modulus E, should be determined with nondestructive inspection such as sonic pulse velocity measurements. If neccessary, cores are taken from bridge for compressive and split test.

Reinforcing steel is assumed to be elastic perfctly plastic material. Actual values of the yield strength f_y and elastic modulus E_s are used. The strain—hardening region may be considered, if neccessary.

The bond stress—slip relationships of Mirza and Houde is used, expressed as[6]:

$$\tau = (54 \times 10^2S\text{-}25.7 \times 10^5S^2 + 5.98 \times 10^8S^2\text{-}0.558 \times 10^{11}S^4\sqrt{f'_c/41.5}) \tag{11}$$

in which τ is the bond stress in MPa, S is the slip in cm.

Interlock elements are employed to model the interface shear transfer across the crack by aggragate interlock and friction. The stiffness of the element is derived from Horde & Mirza's shear stress-displacement relation as[6]:

$$Kg = 63.85(1/C)^{3/2}\sqrt{f'_c/35A} \tag{12}$$

in which A is the area for which one element is responsible, in cm^2; f'_c in MPa; C is crack width in cm; k_g in N/cm.

5. EVALUATING PROCEDURE

Based on the mathematical model and the finite element model aforementioned, a finite element program can be developed and implemented into a particular computer code to simulate the load tests of R. C. bridges. For T—beam bridges, each beam of the bridge is evaluated as a single unit. Simulation results of all beams are synthesized and analyzed to give the resistance factor of the whole bridge. The evaluating procedure is described in the following.

5. 1 Field Survey and Review of Design Documents

A thorough field survey is needed to obtain the information about deterioration of the bridge, including crack location and size, corrosion of reinforcement, actual material properties, and as — built dimensions. The presence and location of reinforcement can be determined though review of design documents. If the design drawings are not available, the reinforcement location may be determined using a pachometer which locate steel magnetically. The parameters needed in the computational model can be defined through field survey and review of design documents.

5. 2 Determination of Loading pattern and Finite Element Meshes

According to loads for evaluation, the most detrimental loading pattern can be decided. The transverse distribution of loads must be taken into account to determine the detrimental loading pattern applied to each beam evaluated. Generally for simply supported beam, the internal forces such as bending moments and shear forces at beam ends and mid—span control the position of loads. After defining the load pattern, finite element meshes are constructed. Data file are prepared and inputed into computer to start simulation of load test using incremental load procedure described in the next.

5. 3 Incremental Loading

For the i th T-beam, the loading factor is defined as w_{ij} in the j th loading increment. If failure occurs or the specified indexes, such as deflection and crack width, are reached at m th loading increment. The resistance coefficient for the beam is defined as:

$$K_i = \sum_{j=1}^{m} W_i j \tag{13}$$

5. 4 Evaluating the Load Carrying Capacity

If the bridge consist of n of beams and the resistance coefficient for every beam is caculated, the resistance coefficient of the bridge is given as:

$$K = \varphi_T \cdot Min(K_1, K_2 \cdots, K_n) \tag{14}$$

where $\varphi_T = 1 - d_T$, φ_T and d_T are integrity and damage of the transverse diaphragms, respectively; k_i(i

$= 1,2,\cdots n$) is the i th beam's resistance coefficient.

If $k > 1$, the load carrying capacity of the bridge is enough to meet the need of present traffic. Otherwise, repairs or rehabilitation must be made to restore or increase the load capacity.

6. EXAMPLE OF BRIDGE EVALUATION

Using the computational model given is this paper, a computer program RCBM for simulaing the load tests of R. C. bridges is developed. The proposed approach is illustrated by an example. The load capacity is evaluated for one beam of a T-beam bridge which is located in chengdu city in China. The bridge, built in 1961, is a three-span simply supported T-beam bridge. The cross section are composed of 12 T-beams. The span length is 16. 3m. The mid-span cross section of one beam is shown in Fig. 5. There are 14 main unnotched rebars which have diameter of 32mm. Concrete design compressive strength is 18. 4MPa. A field survey was conducted. Spalling, corrosion of rebars, several inclined and vertical cracks were found. Actual concrete compressive strengeh is only 8. 3Mpa. One beam was taken from the bridge for failure test in order to judge whether the load capacity is enough or not. The load pattern is shown in Fig. 6 [7].

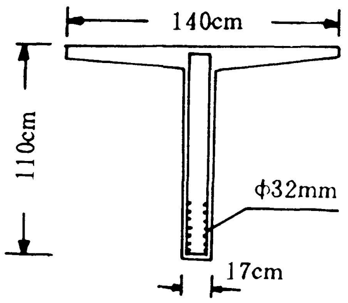


Fig. 5 Mid—span cross section

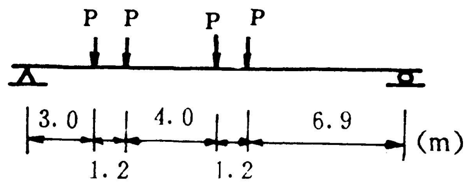


Fig. 6 Loading pattern

The design load p is 70. 5KN, corresponding to the bending moment of 782. 6KN—M in mid—span. The program RCBM is employed to simulate the failure test and evaluate the experimental results as shown in Table 1. The load—mid-pan defletion curves of the beam are shown in Fig. 7. It can be seen, from Table 1 and Fig. 7, that the proposed simulation method gives a good approximation to failure test of the T—beam, the evaluation resuts are available.

Table 1 Comparision of simulation results with test results

	Max. Load(4P) (KN)	Mid—span bending Moment (KN—m)	The resistance coeffcient
Design	282	782. 6	
Simulation	540	1497	1. 91
Test	600	1665	2. 13

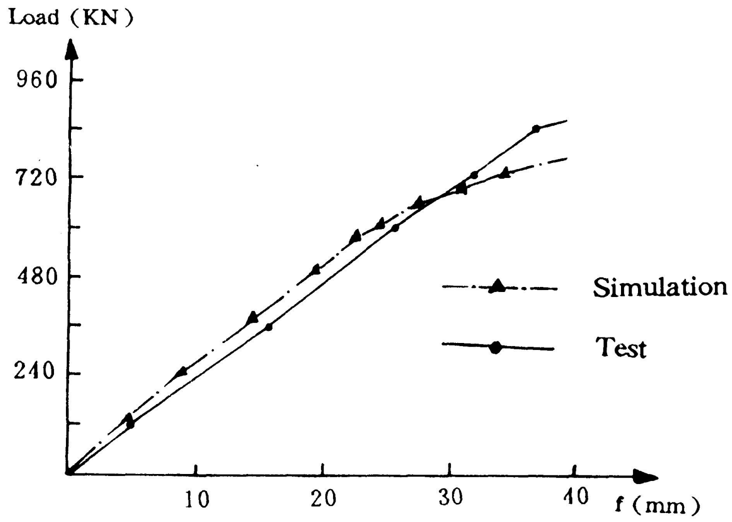


Fig. 7 Load—mid-span deflection curve

7. CONCLUSIONS

—An evaluation method for load carrying capacity of existing bridges should distinct from methods in design of new bridges. A finite element model for evaluating the load capacity is developed, in which the factors influencing the load capacity are taken into account. Nonlinear constitutive relationships and failure criteria under biaxial stresses are employed to explore the realistic load carrying capacity.

—A simulation method is proposed to estimated the load capacity of existing bridges. Using the method, load tests can be simulated in order to given reliable resistance coefficient of the bridge. The method is effective and inexpensive, since it may replace many load tests. Although the present approach is developed for R. C. bridges, it can be used in the evaluation of various types of bridges, such as steel bridges and composite bridges.

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