論文 The Analysis for the Cable Anchorage of Suspension Bridges Based on the Extended Fictitious Crack Approach

Ahmed Saad Eldin MORGAN*1, Junichiro NIWA*2, and Tada-aki TANABE*3

ABSTRACT: In this paper, as the application of the extended fictitious crack approach to simulate a real case study, the analysis of the cable anchorage of suspension bridge, has been carried out. The extended fictitious crack approach which is based on the nonlinear fracture mechanics with two orthogonal rod elements has been employed in this study. The ANACS program, which is originally developed by the authors, has been utilized in its plane stress version. Using the arc-length technique, the post peak behavior of the load-displacement response has been detected.
KEY WORDS: concrete fracture, finite element, discrete model, fictitious crack, rod elements, suspension bridge, cable anchorage

1. INTRODUCTION

After proving the validity of the developed fictitious crack approach to simulate the real behavior of concrete and reinforced concrete structures in two and three dimensional problems [1, 2, 3], we try to apply this technique to estimate the ultimate strength of the cable anchorage which supports the cable suspension bridges.

Figure 1 shows the real geometry of the cable anchorage and its configuration through the concrete block. The material parameters can be chosen according to the concrete parameters in the design mix report.

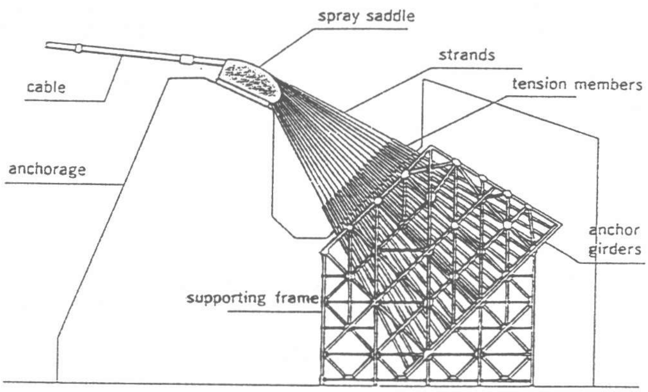

Fig. 1 Schematic diagram for the cable and the concrete block connection

2. THE FINITE ELEMENT MODELING

The four nodded quadrilateral elements and the three nodded triangular elements which are available in the program library have been utilized. The three nodded triangular elements are utilized to simulate the crack path and to define the inclined load application surface.

*1 Department of civil engineering, Nagoya University, Member of JCI
*2 School of civil engineering, Asian Institute of Technology, Dr., Member of JCI
*3 Department of civil engineering, Nagoya University, Prof., Member of JCI

The concrete finite elements around the crack path and all along the connection have an elastic stress-strain relationship in tension as a basic assumption of the fictitious crack simulation [4]. Therefore, the failure crack can be easily localized based on the extended fictitious crack approach.

The concrete element response in compression and the adopted criterion for detecting concrete crushing are described by the bilinear stress-strain curve [1] and the biaxial compression yield surface proposed by Kupfer, et al. [5], respectively.

3. THE EXTENDED FICTITIOUS CRACK SIMULATION IN THE CASE OF THE CABLE ANCHORAGE OF SUSPENSION BRIDGE

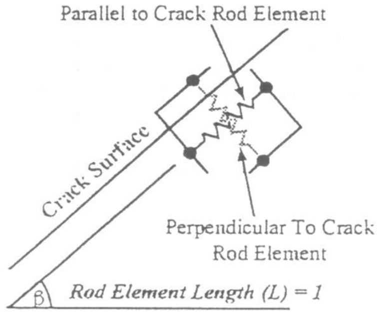

Fig. 2 The rod elements for the failure simulation of cable anchorage

The two orthogonal rod elements (Fig. 2) are used to simulate the crack and represent the localized crack zone. These rods exhibit nonlinear stress-strain behavior of concrete by using the 1/4th softening model [3]. For this concrete, the fracture energy is assumed to remain constant and is determined based on the concrete properties which are available in the report on the concrete mix design.

In this analysis, the fracture energy was calculated from the empirical equation proposed by Bazant [5],

$$G_F = 0.304\,(f_t + 8.95)\,\frac{f_t^2 d_a}{E} \tag{1}$$

where G_F is the fracture energy in *kgf/cm*, f_t is the tensile strength of concrete in *kgf/cm*^{2}, E is Young's modulus of concrete in *kgf/cm*^{2}, and d_a is the maximum size of coarse aggregate in *cm*.

From the report on the concrete mix design, the following values required for Eq. (1) are obtained:

$f_t = 33.9$ *kgf/cm*^{2}
$d_a = 4.0$ *cm*
$E = 3.26 \times 10^5$ *kgf/cm*^{2}

The length of the rod element is assumed as unity (L=1), to change the stress-crack width relationship into stress-strain relationship. The rod elements have been placed between coupled nodes of concrete elements along the predefined crack path, and oriented at some angle β relative to the global coordinate system.

For the perpendicular rod element, the 1/4th model is assigned. The 1/4th model curve is adjusted based on the concrete properties exhibited in the report, where $f_c' = 328$ *kgf/cm*^{2} and G_F is 0.18 *kgf/cm* which is calculated from Eq. (1). The rest of the parameters are taken as mentioned before.

The stress-strain relationship for the rod element parallel to the failure crack surface is taken as linear elastic [2, 3] until the tensile stress in the corresponding perpendicular rod element exceeds the tensile strength of concrete. Thus, when the crack starts at a certain rod element which is perpendicular to the failure crack surface, the resistance of the corresponding rod element parallel to the failure crack surface will vanish. For more explanation refer to references [2, 3].

The ultimate stress value for the rod element parallel to the failure crack surface is chosen to be equal to the tensile strength of concrete exhibited in the report (33.9 kgf/cm^2). This large chosen value reflects that the crack formation and propagation, and the ultimate strength of the cable anchorage of suspension bridges mainly depend on the tensile fracture energy stored in the rod element perpendicular to the crack surface.

4. NUMERICAL SOLUTION TECHNIQUE AND THE CONVERGENCE CRITERION

In this analysis, it is tried to trace the entire load-deformation response of cable anchorage, to know whether the collapse is of a ductile or brittle form. To achieve this goal, the arc-length technique has been utilized.

As for the convergence criterion, an overall convergence criterion "Euclidean norm" has been introduced in the program, which does not depend on particular high unbalanced force, but rather it depends on the overall unbalanced force configuration through the whole structure [3].

However, in this analysis, another convergence criterion has been added. When $\delta\lambda$ value of load variable parameter in the arc-length procedure becomes less than 10^{-5} after many successive iterations, and this very small value has been prevailed in many iterations in one increment step, the program can proceed to the next step, because the load virtually cannot be changed any more when $\delta\lambda$ becomes less than 10^{-5}.

5. THE ANALYTICAL RESULTS FOR CABLE ANCHORAGE OF SUSPENSION BRIDGE

The proposed model to simulate the cable anchorage connection of suspension bridge is illustrated in Fig. 3. The prepared finite element model for the cable anchorage failure simulation, consists of 220 elements including 4 nodded quadrilateral and 3 nodded triangular elements. The number of nodes in this mesh is 249.

Since the fracture energy G_F is kept constant throughout the analysis, then the mesh sensitivity is considered to be insignificant and the relationship between the crack length and the released fracture energy will be the same for any parametric study.

As illustrated in the schematic diagram of Fig. 4, the tendons and the tendon fixation truss have not been modeled. Also, the tendon fixation base has not been modeled, but the diagonal forces exerted from the tendons are modeled to apply on the concrete block as horizontal and vertical distributed loads as shown in Fig. 4. The failure crack surface is assumed as a discrete crack surface running from the edge of the anchor fixation base till the top surface of the concrete block (Fig. 4). In this analysis, the boundary conditions shown in Fig. 4 are considered.

The inclination angle of the diagonal failure surface will be determined based on the extensive parametric study. Six different inclination angles for the crack surface are considered, such as $\beta = 72, 59, 51, 45, 40$ and 36 degrees, then 6 finite element meshes are rearranged accordingly for every considered inclination angle to cover all crack inclination possibilities. The results of this parametric study are shown in Fig. 5. It has been found that the inclination angle of the failure crack surface which gives the minimum strength is ranging between 45 to 36 degrees. Based on the adopted way of numerical analysis which incorporates the fracture energy through the rod elements modeling along the crack path, the following conclusions can be obtained. Figure 5 shows that the ultimate strength is increasing with the increase in the crack inclination angle β up to 60 degrees and also the increase in the corresponding surface angle of the concrete block ϕ. This means that in the case of taking more steeper ϕ and keeping all the other geometric parameters unchanged as they are, the ultimate strength of the cable anchorage will increase. Consequently, the concrete volume, which is required for the structure stabilization in the design practice, can be reduced. By using smaller concrete blocks for such cable anchorage end fixation, the construction cost can be significantly reduced.

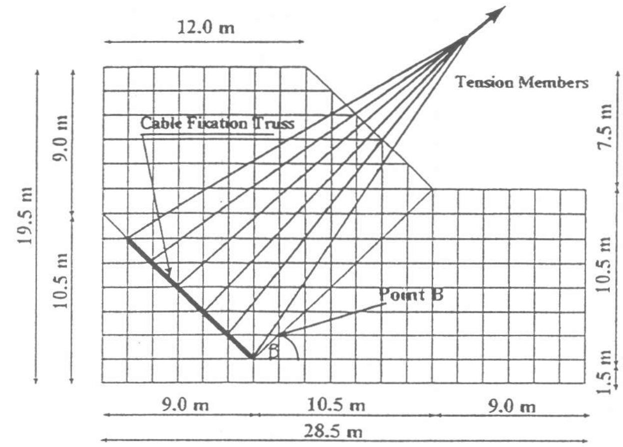

Fig. 3 Typical mesh for the cable anchorage connection (case of crack inclination angle β= 45 degree)

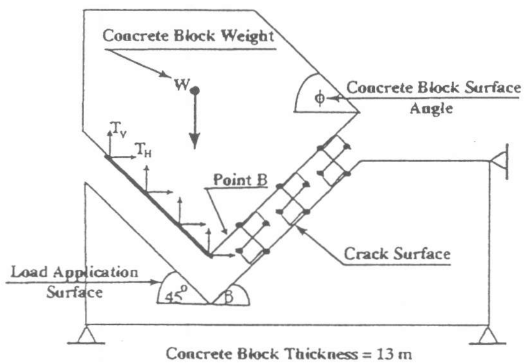

Fig. 4 Schematic diagram to illustrate the failure surface, and the boundary conditions

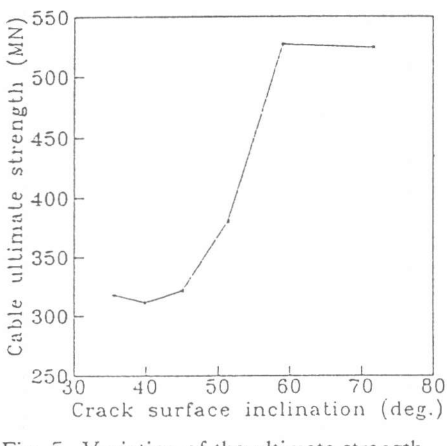

Fig. 5 Variation of the ultimate strength with respect of the crack inclination angle β

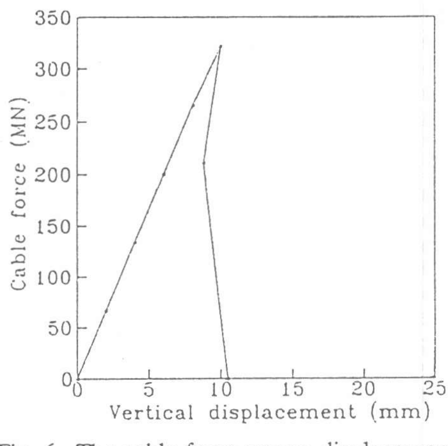

Fig. 6 The cable force versus displacement in the case of the crack inclination angle β = 45 degree

Figure 6 shows the full load-displacement relationship obtained from the case of β = 45 degree, which is similar to the actual structure.

When the maximum strength is attained, a macrocrack develops which becomes wider with the increase in the imposed loads. However, the concrete directly beside this crack behaves in a practically linear elastic manner.

According to Fig. 6, a post peak snap-back response, which reflects the brittle behavior of such cable anchorage, can be observed. As a result of a sudden bifurcation process which leads to a sudden drop in both load and deflection, the snap back phenomenon occurs. This type of failure is very brittle. Moreover, during the analysis of this case, many smaller load increments near the peak load were tried, but the structure cannot sustain any small load increments beyond the existed peak strength, and the load-displacement response starts to turn down. Also, it is better to mention that the detected point for examining the vertical upward displacements in Fig. 6 is the point B in Figs. 3 and 4.

Furthermore, Figs. 7-9 show the deformed shapes of the cable anchorage concrete block at the ultimate strength and at the first and second increment after the peak load, respectively, in case of β = 45 degree.

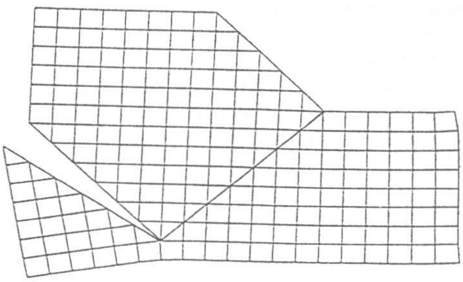

Fig. 7 Deformed shape at the peak load

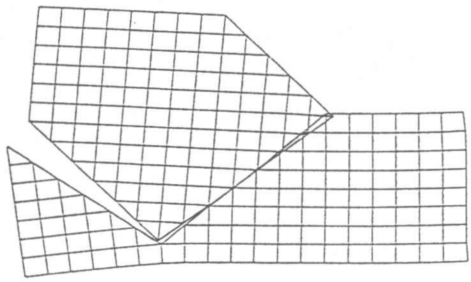

Fig. 8 Deformed shape at the first increment after the peak load

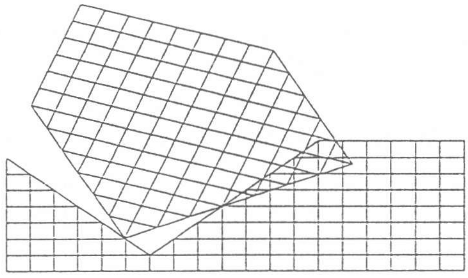

Fig. 9 Deformed shape at the second increment after the peak load

It can be noticed that the vertical displacement at point *B* in Fig. 7 is smaller than that of Figs. 8 or 9, which illustrates the effect of the snap back phenomenon. From Figs. 8 and 9, we can notice that in the cable anchorage failure, the crack opening is much larger than the crack sliding, which reflects that this kind of failure is a matter of mode I fracture of concrete.

For Figs. 7-9, the deformed shapes are drawn with a magnification factor equal to 100. As far a rather large magnification factor was utilized, which converts the small deformations to be large, therefore, the deformed elements were overlapped as shown in Figs. 8 and 9.

6. CONCLUSIONS

It is possible to study the influence of different variables on the ultimate strength of cable anchorage of cable suspension bridges analytically by means of nonlinear fracture mechanics.

It has been observed that the inclination angle of the failure crack surface which gives the minimum strength is ranging between 45 to 36 degrees. Also, it is noticed that the ultimate strength is increasing with the increase in the crack inclination angle up to 60 degree and also the increase in the corresponding surface angle of the concrete block ϕ. In other words, the ultimate strength of the cable anchorage can be increased by taking more steeper ϕ and keeping all other geometric dimensions unchanged as they are. Based on the previous findings, the concrete volume, which is required for the structure stabilization in the design practice, can be reduced, and consequently the construction cost. On the other hand, for flatter crack inclination angle, and also corresponding flatter ϕ, the ultimate strength will be decreasing. Therefore, the decrease in the surface angle of the concrete block ϕ is not recommended from the view point of the ultimate strength.

The failure of this type of connections has been found very brittle with the snap-back response which appeared in the load-displacement diagram. Also, it has been found that the failure of this type of connections is of mode I fracture of concrete.

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