V - 344 A Fracture Mechanics-Based Design Method for SFRC Tunnel Lining

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1. Introduction : Recently, a new design provision for SFRC tunnel lining was published in Japan. It is based on the concept of fracture mechanics of concrete. The existence of a crack and transmitted stress by fibers are considered in the estimation of the maximum resultant forces of the critical cross section. The provision provides a test method of a small specimen and an estimation method for the sectional capacity of the real size problem. In the present paper, these two procedures of the current design method are studied. Some points to be improved are shown and a modified design method is proposed.

2. Fracture mechanics-based design provision for SFRC tunnel lining : The Extruded Concrete Lining, ECL, has been recently introduced in Japan. Extensive use of steel-fiber-reinforced concrete is considered for the lining due to its better capacity in tensile resistance. In the design of the tunnel lining, one of the limit state is the failure of section after initiation and propagation of a crack. Due to the stress transmission across crack surfaces by fibers in the steel-fiber-reinforced concrete, an increase in maximum resultant forces and large toughness after peak load are expected in the lining. To reflect such benefits of steel fibers in design, a new design method is required to replace the conventional method which ignores resistance to tensile stress.

In 1992, "Recommendation for Design and Construction of Extruded Concrete Lining Method" was published by Japan Railway Construction Public Corporation [1]. It is based on the concept of fracture mechanics of concrete. The main assumptions employed in this design provision in the estimation of the maximum resultant forces of the critical cross section are that the maximum crack length is limited to 70% of the thickness of the lining and the transmitted stress along the crack is constant (see Fig. 1). In the current design method, the design constant transmitted stress or design tensile strength carried by fibers is specified to be determined from a bending test with a procedure recommended in the code. The bending test is usually done with a small specimen. From the result of the experiment, the capacity of the real size specimen is predicted. This procedure has to take size effects into consideration.

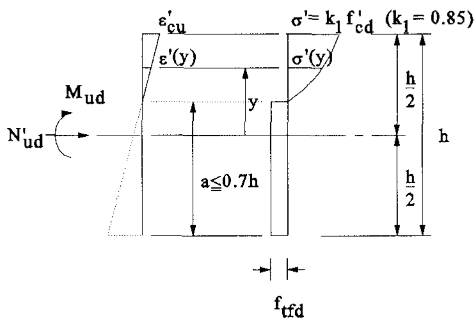

Fig. 1 Estimation method for sectional capacity

3. Stress distribution along critical section : In this section, the stress distribution along the critical cross section at the peak load is investigated. The investigation includes the stress distributions of samples with different sizes and the effects of applied axial compressive force to the stress distribution. The calculation is based on material properties and a tension-softening curve shown in [2]. The tension-softening curve used is obtained from the back analysis method [2] which is a method to obtain a tension-softening curve from a bending test. The FEM with a cracked element [2] is employed in the numerical analysis. The stress distributions are shown in Fig. 2 and 3. From the figures, it can be seen that the assumption of constant transmitted tensile stress along the crack is reasonable for small axial force cases. However, the crack length, at the peak load, greater than 70% of the thickness is also found, and it varies according to the size of the specimen and the axial compressive force. Thus, the assumption using the maximum crack length equal to 70% of the thickness needs careful consideration.

4. Proposed design method : Because it is found that the assumption of constant transmitted stress is reasonable, this assumption is adopted by the present study. Nevertheless, the assumption of maximum crack length equal to 70% of the thickness is not employed. It is known that the shorter crack length results in the smaller moment resistance. Therefore, the maximum crack length equal to 70% of the thickness which is less than crack lengths obtained from the FEM leads to the conservative prediction of the sectional capacity. But

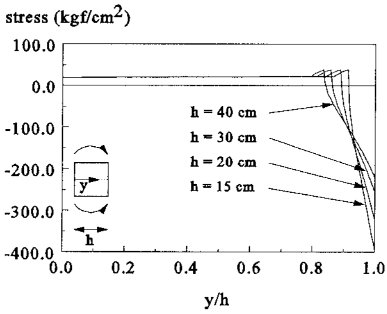

Fig. 2 Stress distribution along the critical section of samples with different sizes

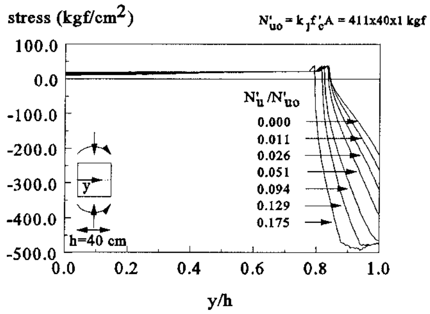

Fig. 3 Stress distribution along the critical section for different axial forces

in the estimation of the tensile strength carried by fibers, this assumption will give an overestimated prediction. In the current design method, the ultimate moment of a small beam is measured, and the design stress distribution shown in Fig. 2 which employs the assumption of maximum crack length equal to 70% of the thickness is used in the calculation of the tensile strength carried by fibers. Hence, the tensile strength carried by fibers obtained by the current design method is overestimated if the real crack length is greater than 70% of the thickness. In the present study, the crack length is not fixed in the estimation of the tensile strength carried by fibers. Instead, the axial compressive strain at the top of the critical section at the peak is used in the calculation. Thus, the quantities that must be obtained from an experiment are the ultimate moment and compressive strain at the top of the beam at peak. Fig. 4 shows the tensile stress distribution obtained by the FEM. It is compared with the constant tensile strength carried by fibers obtained by the present study and the current design method. It is seen that the present study shows good estimations, both for crack length and transmitted stress, while the current design method gives an overestimated transmitted stress.

Next, the capacity of the real size is predicted. It is found that it is reasonable to use the tensile strength carried by fibers obtained by a small specimen directly for bigger specimens [2]. The crack length must be provided for the estimation. In this study, many crack lengths have been tried. Fig. 5 shows the interaction diagrams obtained by the FEM and the predictions with different crack lengths. It is found that if the maximum crack length is limited to some appropriate values less than the real crack length, a good prediction can be obtained. The real crack length varies with respect to the size of the specimen, the slope of the tension-softening curve and also the magnitude of the applied axial compressive force. A procedure to obtain the appropriate crack length used in the prediction of the sectional capacity is proposed in [2].

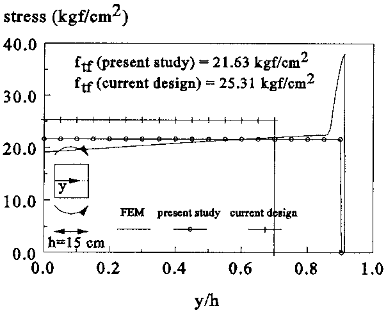

Fig. 4 Tensile strength carried by fibers

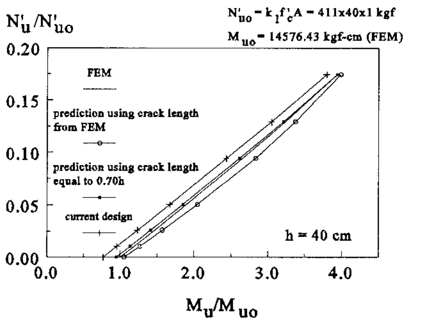

Fig. 5 Predicted interaction diagram

5. References

[1] Japan Railway Construction Public Corporation (1992), Recommendation for Design and Construction of Extruded Concrete Lining Method, [available at Yoshii Shoten, 3-7-11 Iidabashi, Chiyoda-ku, Tokyo 102].

[2] Nanakorn, P. (1993), Fracture Mechanics Based Design Method of SFRC Tunnel Lining, Doctoral Dissertation, The University of Tokyo.