3. SERVICEABILITY LIMIT STATE

3.1 Flexural Crack Width of RC Beams

3.1.1 Limit State on Crack Width

In a general design of RC structures, the tensile stress of concrete is neglected and the reinforcement is provided to resist all tensile forces arising in a section. Normally cracking of concrete does not directly lead to the failure of RC structures. However, in the case of design which has to consider the tensile resistance of concrete such as plain concrete structures, the failure of such structures is highly related to the cracking of concrete. Even in the case of RC structures, when they are subjected to relatively low shear forces, the tensile resistance of concrete is expected implicitly and hence diagonal cracking becomes serious. In addition, in the anchorage zone of a deformed bar, since the tensile resistance of concrete is taken into account, it is necessary to pay attention on cracking along the bar.

In the case of RC structures subjected to flexure under the service loads, cracks occur in the flexural tension zone of the section. The excessive crack width leads to unfavorable consequences as follows:

(1) Due to the penetration of water and air through the crack, the corrosion of reinforcement inside the concrete occurs. This will increase the volume of reinforcing steel and spall the concrete cover out. The rate of corrosion of uncovered reinforcement increases very rapidly. The corrosion of concrete deteriorates not only the appearance of structures but also the durability of concrete structures.
(2) In the design of structures with special attention on air as well as water tightness, the function of the structure will be lost if a crack having excessive width occurs.
(3) In the aesthetic view point, excessive crack is undesirable.

So, it is required to determine the limit state on crack width of RC structures.

The reinforcement inside the concrete with relatively good quality will not be corroded. In general, RC structures are considered to be very durable compared with other types of structures. In spite of cracking of concrete, the corrosion of reinforcement will not occur if the concrete cover is sufficiently thick, and the surface crack width is less than a limit value. Since the limit state on crack width is related to the durability of concrete structures and not to the failure, it is considered as one of ***the serviceability limit states.***

3.1.2 Permissible Crack Width

A permissible crack width of the concrete surface is determined depending on the environmental conditions where RC structures are exposed. The corrosion of reinforcement is affected by not only the crack width at the surface of concrete but also the distance between the surfaces of concrete and reinforcement. Hence, the concrete cover which is defined as the distance between the surfaces of concrete and reinforcement becomes an important parameter concerned with the corrosion of reinforcement. From various experimental results, the degree of corrosion of reinforcement in the case of the same concrete cover is almost the same, and more corrosion occurs in the case of less concrete cover.

The surface crack width decreases when the concrete cover is reduced. However, the reduction of concrete cover leads to more corrosion of reinforcement.

Considering the relationship between corrosion of reinforcement, surface crack width, and concrete cover, in the JSCE Specification the surface crack width is examined to be less than a permissible value which is a function of concrete cover. In the JSCE Specification, the permissible crack width, depending on environmental conditions, concrete cover, and type of reinforcement, is stipulated (Table 3.1, Table 3.2).

Table 3.1 Classification of environmental conditions

Normal environment	Outdoors of ordinary condition where chloride ions do not come, underground, etc.
Corrosive environment	1. As compared with normal environment, reinforcement subjected to detrimental influences, such as severe alternate wetting and drying, and structures below the level of underground water containing harmful substances 2. Marine structures submerged in seawater and structures exposed to mild marine environment, etc.
Severely corrosive environment	1. Reinforcement subjected to detrimental influences considerably 2. Marine structures exposed to tides, sprashes, severe ocean winds, etc.

Table 3.2 Permissible crack width , w_a (mm)

Type of reinforcement	Environmental conditions for corrosion of reinforcement		
	Normal environment	Corrosive environment	Severely corrosive environmenat
Deformed bars and plain bars	0.005C	0.004C	0.0035C
Prestressing steel	0.004C	-------	-------

In Table 3.2, "C" is concrete cover (mm). For the case of C > 100 mm, C = 100 mm. In Table 3.2, the permissible crack widths for prestressing steel in corrosive environment and severely corrosive environment are not determined. It is considered that prestressed concrete can be designed prohibiting the formation of flexural cracks by using prestressing, and that it is necessary to examine the corrosion of prestressing steel much more carefully. It is advisable to design the prestressed concrete member prohibiting the formation of cracks in such environmental conditions.

3.1.3 Prediction of Flexural Crack Width

(1) Derivation of equation for predicting flexural crack width

When the flexural moment is applied to RC beams, a flexural crack due to flexural tensile stress occurs at the extreme tension fiber. Then, as the moment is increased, the number of cracks increases and the *crack spacing* gets smaller. This will cause the tensile stress in concrete between the adjacent cracks. After the initiation of number of flexural cracks, new cracks are hardly formed because of a relatively short development length for bond stress. Hence, *the stable state of cracking* is obtained. At this stage, cracked portion around the tensile reinforcement in a flexural member can be considered to be equivalent to a concrete member having a single reinforcement subjected to pull-out force at both ends (Fig. 3.1).

Denote l as the crack spacing. From the equilibrium of forces at the mid section between cracks, the following relationship can be derived:

$$\int_0^{l/2} \tau_b(x)\,U\,dx = \overline{\tau_b}\,U\,\frac{l}{2} = \overline{\sigma_{ct}}\,A_e \qquad (3.1)$$