- Technical Paper -

QUANTITATIVELY EVALUATION OF CRACK PROPAGATION DUE TO REBAR CORROSION

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ABSTRACT

Cracking behavior due to rebar corrosion for concrete specimen with single rebar was evaluated analytically. The evaluation was performed by comparing with results of the electric corrosion test. Three-dimensional Rigid-Body-Spring-Method (RBSM) with three phase material corrosion expansion model was applied to simulate internal cracking patterns and surface crack width propagation. The effect of rebar local corrosion and penetration of corrosion products into cracks during the corrosion process were investigated and cracking behavior due to rebar corrosion was evaluated quantitatively.

Keywords: Rigid Body Spring Model, Local Corrosion, Penetration of corrosion products, Expansion Model, Crack Width, Internal Crack

1 INTRODUCTION

Cracking of concrete due to rebar corrosion is one of the major deterioration behaviors and it causes the spalling of concrete cover or acceleration of deterioration. It is necessary to predict the internal damage from the observable surface condition during maintenance process. Therefore, it is desirable to establish a prediction method to quantitatively assess the internal crack propagation behavior and rebar corrosion rate from surface cracks. The internal crack patterns due to rebar corrosion considering the difference of cover thickness or diameter of reinforcing bar has been clarified [1] and [2]. The propagation of surface crack width against corrosion rate was also studied [3], [4] and [5]. Kawamura [3] could simulate reasonably qualitative behavior of the cracking of single rebar specimen but the quantitative behavior was overestimate when it was compared with the testing results. Moreover, the effect of local corrosion and local penetration of corrosion products into cracks after the cracking initiation has not been clarified in the literature.

In this study, the crack propagation behavior is analyzed quantitatively. The crack propagation behavior is simulated using Rigid-Body-Spring-Method with three-dimensional Voronoi particles. In the analysis, the three phase material model which consists of rebar, corrosion products layer and concrete is applied. For the corrosion products layer, the effect of corrosion products is considered by initial strain problem due to corrosion expansion. Moreover, the local corrosion of rebar and the effect of penetration of corrosion products into cracks after the cracking initiation are simulated. The applicability of the model is verified by comparing with the testing results. As the results, the progress of surface crack width, the propagation of internal cracks, the effect of local corrosion and the local penetration of corrosion products into cracks and so on are clarified.

2 EXPERIMENTAL STUDY

2.1 Testing method

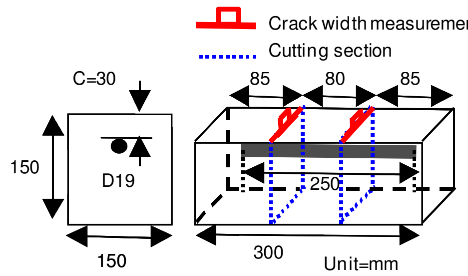

Figure 1. Specimen setup

Figure 1 shows the specimen set up of the electric corrosion test [3] and [6]. The corrosion process was accelerated by using external direct current as shown in the Figure 2.

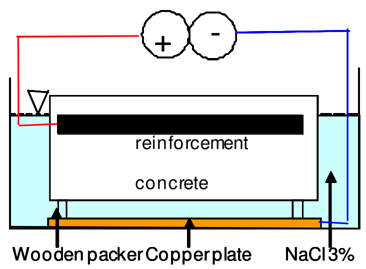

Figure 2. Schematic of corrosion test

2.2 Experimental crack patterns

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Figure 3 indicates the defined internal crack types shown in crack patterns.

Internal crack patterns at several corrosion rates are shown in Figure 4 which correspond to the marked points in Figure 5. Initiation of visible crack occurs on the surface of concrete cover (vertical crack). When corrosion products increase, the crack propagates inside the concrete cover. After that, lateral cracks appear and their lengths increase.

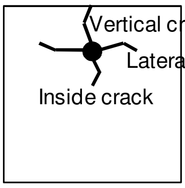


Figure 3. Internal crack types

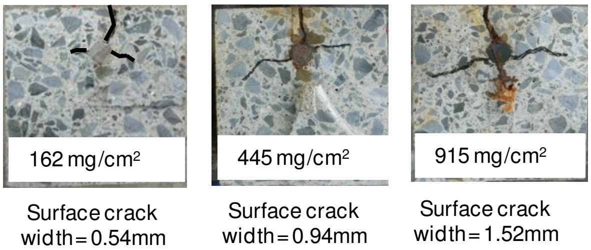


Figure 4. Internal crack patterns

2.3 Surface crack width propagation

Propagation of surface crack width against corrosion rate is shown in Figure 5. It can be seen that opening of surface crack initiates after a significant amount of corrosion products are formed. After the initiation, surface crack width propagates rapidly up to the value about 0.4mm. After that, the speed of propagation reduces with occurrence of lateral cracks and effect of penetration of corrosion products into cracks to be discussed in the later part of this study. Finally, the speed of propagation increases again with the further propagation of the lateral crack.

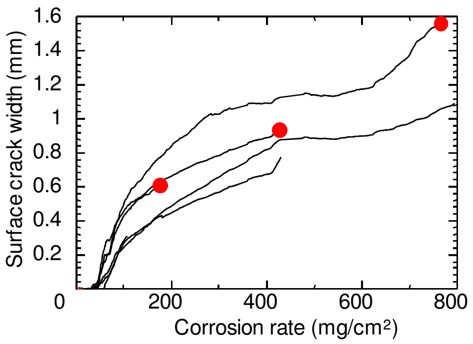


Figure 5. Surface crack width propagation

3 ANALYTICAL MODEL

3.1 Three- dimensional RBSM

Rigid- Body-Spring-Method (RBSM) is one of the discrete approaches and it is easy to deal with crack propagation of concrete directly. The method represents a continuum material as an assemblage of rigid particle elements interconnected by zero springs along their boundaries (Figure 6). In this study, three-dimensional RBSM is applied [7]. Each element has six degrees of freedom at center points. Boundary between two elements is divided into triangles formed by the center and vertices of the boundary. At each center point of triangle, three springs, one normal and two shear springs are set. The analytical model is divided into elements using Voronoi random polygons. In RBSM model, crack widths can be automatically measured during the analysis. The three-dimensional model is possible to simulate complicated problems.

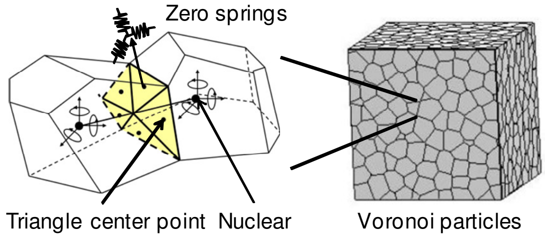


Figure 6. RBSM Voronoi polygons

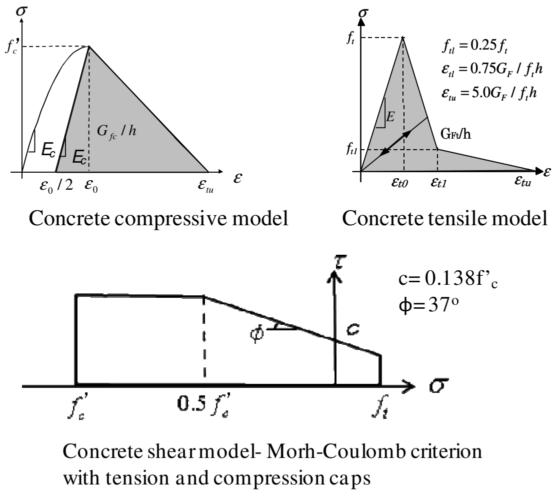


Figure 7. Concrete material model

3.2 Material models

Figure 7 shows concrete material models used in analysis.

In the compressive model, f'_c is compressive strength of concrete, G_{fc} compressive fracture energy, E_c is Young modulus of concrete.

The tensile behavior of concrete up to the strength is modeled by using linear elastic. While bilinear softening branch of 1/4 model is assumed after cracking as shown, in which f_t is tensile strength, G_{ft} is tensile fracture energy and h is distance between centers of Voronoi elements.

Tangential springs represent the shear transferring mechanism of concrete. The shear strength is assumed to follow the Morh- Coulomb type criterion with the tension and compression caps. The shear fracture criterion is expressed as follows [8]:

$$\frac{\tau^2}{\tau_f^{\ 2}} \geq 1 \qquad (1)$$

where $$\tau_f = \begin{cases} c - \sigma \tan\phi, \ for \sigma \geq 0.5 f'_c \\ c - 0.5 f_c \tan\phi, \ for \sigma < 0.5 f'_c \end{cases} \quad (2)$$

Rebar is modeled as linear elastic.

3.3 Corrosion expansion model

Modeling expansion of corrosion products is shown in Figure 8. Three phase material model including rebar, corrosion products and concrete is applied. The merit of the model is that the properties of corrosion products such as thickness (H) and elastic modulus (E_r) are assumed directly. The model is efficient to investigate the effect of corrosion products. In the model, initial strain is gradually increased in normal springs located on boundary of the corrosion products layer based on initial strain problem.

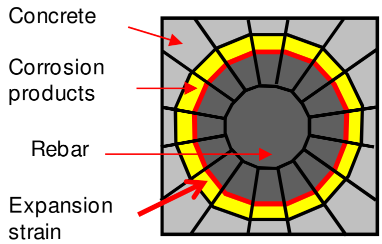


Figure 8. RBSM corrosion expansion model

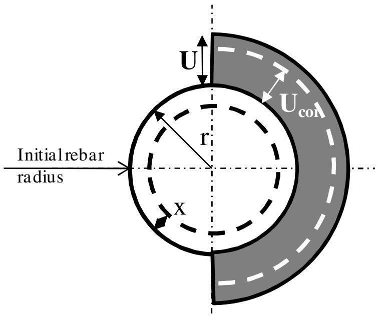


Figure 9. Deformation around rebar due to corrosion products

Lundgren [4] and Oh [9] suggested a model of deformation around rebar due to corrosion products which can be described in Figure 9, in which r, x, U and U_{cor} are initial radius of rebar, corrosion penetration depth, free increase of the radius and the real increase of the radius respectively. The strain in the corrosion products is

$$\varepsilon_{cor} = \frac{U_{cor} - U}{x + U} = \varepsilon_{real} - \varepsilon_{free} \quad (3)$$

In RBSM model, initial thickness of corrosion products layer is modeled constantly as H so

$$\varepsilon_{free} = \frac{U}{H} \quad (4)$$

This parameter is input data in the analytical program by increasing the corrosion rate. U is computed from the corrosion rate as the following equation [10]

$$U = \frac{W_r (dV - 1)}{\rho_s} \quad (5)$$

where W_r is corrosion rate (mg/cm^2), dV is volume expansion ratio of corrosion products which depends on corrosion product that forms [4]. In this study, it is assumed as 2.5 [10], ρ_s is rebar density (=7.85x10^3 mg/cm^3).

It is not easy to measure properties of corrosion products such as thickness and elastic modulus by experiment. In this study, the initial thickness of 1.0mm and the elastic modulus of 500MPa are recommended because they can simulate the cracking behavior reasonably in comparison with the experimental results.

4 UNIFORM CORROSION MODEL

In this model, it is assumed that corrosion products are uniformly formed around rebar before and after the cracking initiation.

4.1 Internal crack patterns

Analytical crack patterns at several values of the surface crack widths are obtained as shown in Figure 10. The analytical internal crack patterns appear to be similar to the experimental ones. However, at the high levels of corrosion products amounts, the analytical ones show inside cracks propagating from the rebar clearly but the testing results do not show this crack. The difference may be due to the assumption of uniform corrosion in the analysis.

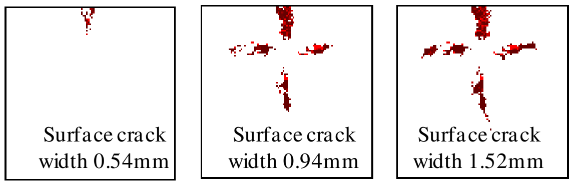


Figure 10. Internal crack patterns

4.2 Surface crack width propagation

Analytical surface crack width propagation in the case of uniform corrosion model is compared with the experimental results in Figure 11 (black line).

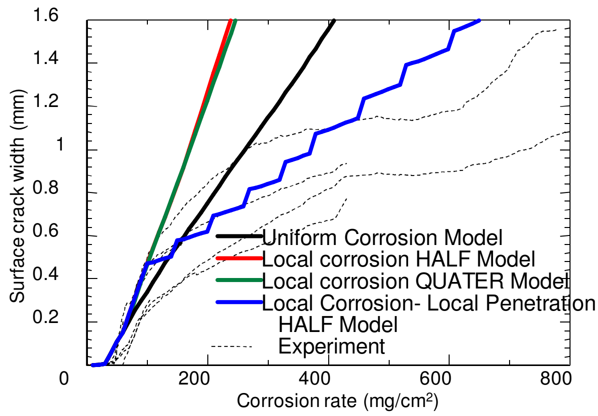


Figure 11. Surface crack width propagation

The analytical results appear similarity with the experimental results, i.e. crack width initiating after a certain amount of corrosion products and then crack opening propagating speedily up. However, analytical crack width values are larger than the experimental results, especially when corrosion rates increase. Reason of the difference is corrosion products tending to penetrate into cracks after cracking initiation which reduces expansive pressure onto concrete. This effect will be discussed in detail later in this study.

5 EFFECT OF LOCAL CORROSION

5.1 Local corrosion model

Chloride diffusivity coefficient through cracked concrete is much more than through the sound concrete [11]. As the results, the rebar is much more corroded around the crack than the other part surrounded by un-cracked or minor cracked concrete.

Figure 12 shows experimental results of local corrosion of the rebar accordingly to the internal crack patterns shown in Figure 4. Local corrosion can be observed near the vertical crack.

162 mg/cm² Surface crack width=0.54mm | 445 mg/cm² Surface crack width=0.94mm | 915 mg/cm² Surface crack width=1.52mm

Figure 12. Local corrosion

In this study, local corrosion of rebar after cracking initiation is simply assumed as follows:

- Rebar is locally corroded when vertical crack near rebar exceeds 0.1mm width.
- Local corrosion model is QUARTER corrosion model or HALF corrosion model as shown in Figure 13.
- At the same corrosion rate, total amount of corrosion products in the local corrosion model (S_L) is the same as the one in the uniform model (S_u).

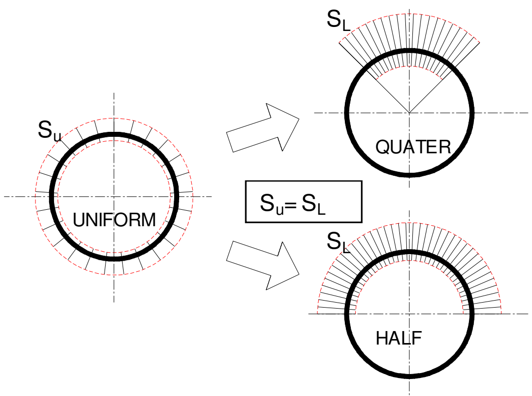
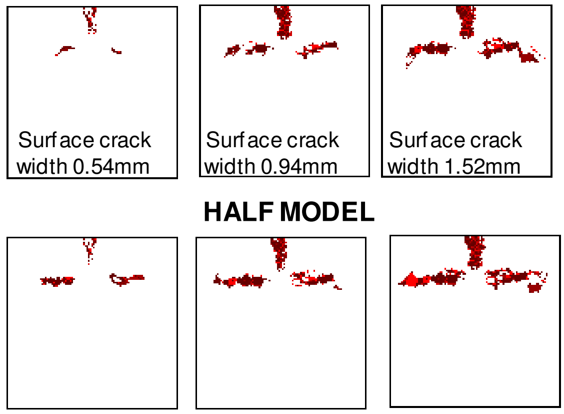


Figure 13. Local corrosion models

Based on the above assumption, the free increase U of corrosion products layer is re-calculated for each local corrosion model. That is the strain in the corrosion products are 2 times or 4 times of the uniform corrosion model for the HALF and QUARTER corrosion models.

5.2 Internal crack patterns

Figure 14 shows internal crack patterns of the HALF corrosion model and the QUARTER corrosion model.



QUATER MODEL

Figure 14.Local corrosion-int. crack patterns

It can be seen that the analytical crack patterns are similar in the two cases of the local corrosion and they are reasonably agreement with the testing results in Figure 4.

5.3 Surface crack width propagation

Analytical surface crack width propagations are also shown in Figure 11 where red line for HALF model and green line for QUARTER model. The surface crack width propagations in two local corrosion models are similar. When rebar is corroded, the concrete cover is bended due to internal expansion pressure and the tensile stress is maximum on the cover surface just above the rebar [3] and [5]. With the same amount of corrosion products formed around rebar only in the concrete cover thickness, the surface crack opening will propagate similarly.

The surface crack width in the local corrosion models is larger than the one in the uniform corrosion model at the same corrosion rate. It is due to more amount of corrosion products formed in the concrete cover thickness in the local corrosion models than in the uniform model.

6 EFFECT OF PENETRATION OF CORROSION PRODUCTS INTO CRACKS

6.1 Penetration of corrosion products

During the corrosion process, it is known that corrosion products tend to penetrate into cracks after the cracking initiation (Figure 15). This effect may reduce corrosion expansion pressure on concrete accordingly [12] and [13].

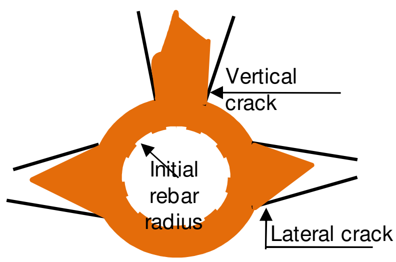


Figure 15. Penetration of corrosion products into cracks

Experimental results also show that corrosion products mainly penetrate into cracks in the concrete cover thickness rather than the lateral cracks since local corrosion occurs due to the effect of vertical crack. Moreover, part of corrosion products also move out the surface of specimen (Figure 16).

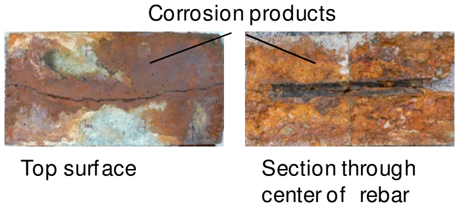


Figure 16. Local penetration of corrosion products into cracks

In order to simulate this effect in the analysis, some assumptions are made as follows:

- Corrosion products can only penetrate into cracks if crack width is larger than 0.1mm
- Corrosion products fully fill in the cracks
- Only cracks above the plane at center of rebar are taken into account. That is, only the penetrations to vertical cracks are taken into account.

Volume of cracks can be directly calculated in the analysis as shown in Figure 17.

When the penetration of corrosion products into cracks is considered, the effective corrosion products volume $V_{cor,eff}$ is:

$$V_{cor,eff} = V_{cor} - V_{crk} \quad (6)$$

where V_{cor} is volume of corrosion products in the corrosion model and V_{crk} is volume cracks as computed in Figure 17.

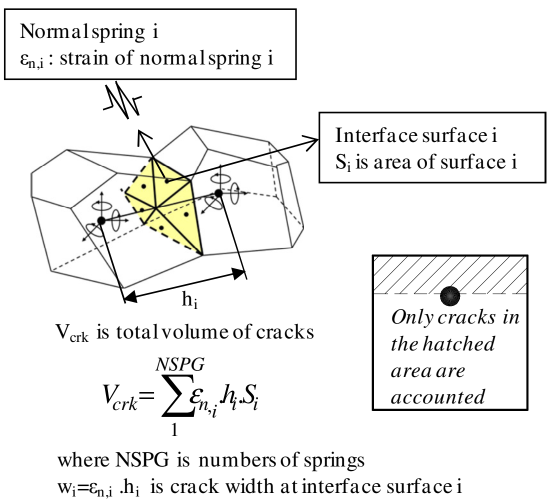


Figure 17. Computation volume of cracks to simulate penetration of corrosion products into crack

The reduction of the free increase of the corrosion products layer is calculated from the effective corrosion products volume.

In the analysis, the local penetration model is combined with HALF local corrosion.

6.2 Surface crack width propagation

The analytical surface crack width propagation in the case of HALF local corrosion model combined with local penetration model is also shown in the Figure 11 (blue line). It can be seen that when the penetration of corrosion products into cracks are taken into account, it can be simulate the crack propagation closely to the testing results in both of the values of surface crack width and the tendency of opening speed of the surface crack width.

It is noted that analytical internal crack patterns in this case are the same as the ones of HALF local corrosion model shown in Figure 14.

7 PROPAGATION OF INTERNAL CRACKS

7.1 Propagation of crack width of vertical crack near rebar

Figure 18 shows the propagation of vertical crack width near rebar in the cases of local corrosion HALF model (black line) and local corrosion model combined with local penetration model (red line). When the effect of penetration of corrosion into cracks is taken into account, the analytical results appear to be closely to the testing results.

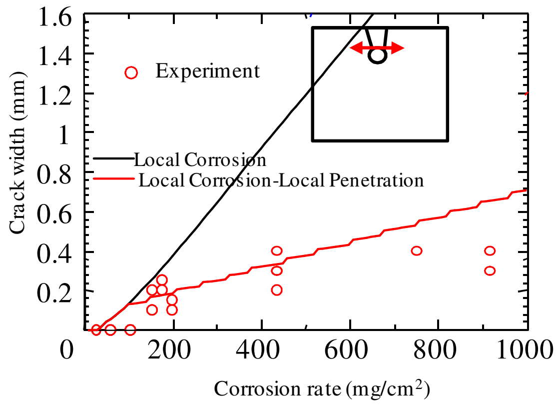


Figure 18. Propagation of vertical crack width near rebar

7.2 Propagation of lateral crack length

The analytical lateral crack length propagation in the cases of local corrosion HALF model (black line) and local corrosion model combined with local penetration model (red line) are shown in Figure 19. The tendency of analytical result is similar to the testing results. The propagation of lateral crack length is also closer to the experiment when the penetration effect is considered.

7.3 Propagation of lateral crack width

Figure 20 shows propagation of lateral crack width at several positions from rebar in the cases of local corrosion and local corrosion combined with local penetration respectively. Red and black lines represent positions at 10mm and 40mm from rebar. With the same color, solid lines represent the combination case and dashed lines do for the local corrosion case. Again, when the effect of penetration of corrosion products is taken into account, lateral crack widths can also be simulated reasonably against the experimental results.

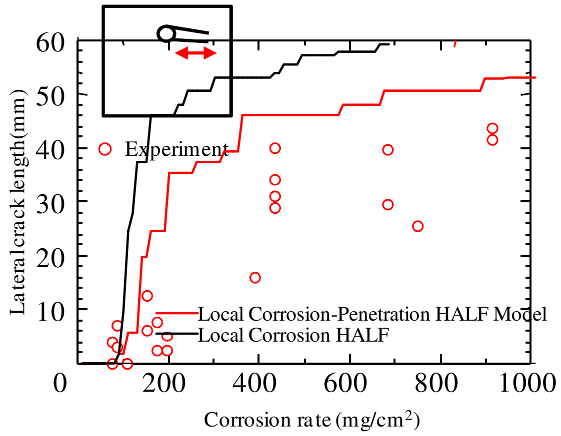


Figure 19. Propagation of lateral crack length

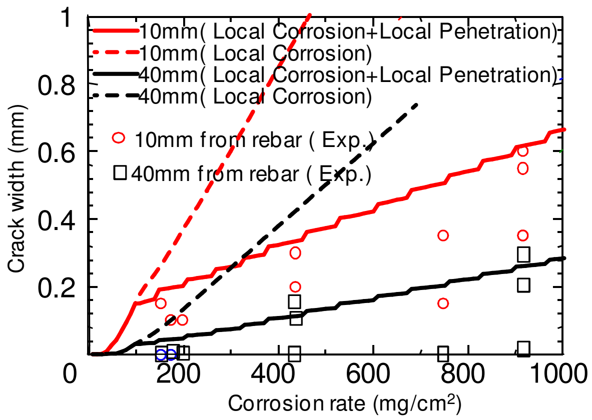


Figure 20. Propagation of lateral crack width

8 CONCLUSIONS

(1) 3D- RBSM analytical model was applied to evaluate cracking behavior of the concrete specimen with single rebar. Internal crack patterns, surface crack width propagation and internal crack propagation were simulated and compared with the experimental results. The model of local corrosion after cracking initiation and local penetration of corrosion products into cracks during corrosion process was proposed.

(2) When the local corrosion model is taken into account, it can simulate the internal crack patterns reasonably.

(3) When the local corrosion model is combined with the local penetration model of corrosion products into cracks, they can simulate reasonably internal crack patterns and quantitatively surface crack width propagation as well as internal crack propagation in comparison with the testing results.

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