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Empirical Model for Evaluation of Concrete Corrosion Current Density

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Abstract

In health evaluation of existing concrete structures, the state of reinforcement corrosion needs to be ascertained without causing distress to the structure, and one indirect approach is to correlate the resistivity of concrete to the corrosion current density and thus to the corrosion. Three models reported in literature are analyzed in this paper for their accuracy, and a new approach with different models for different ranges of resistivity are proposed which performs with better accuracy. The strengths and the limitations of the different models are discussed.

Keywords: Corrosion current; Concrete resistivity; Reinforcement corrosion.

1. Introduction

Over the last few decades, the corrosion of steel in concrete has caused numerous costly repairs and many structural failures. More details may be found in Bertolini et al. [1]. Assessment of the corrosion process has become important not only for evaluation of health of existing structures but also for the design of new structures. In-service health monitoring of reinforced concrete structures are gaining importance day by day, especially for the existing important infrastructures exhibiting some distress signs. The focus is on achieving the evaluation of the health of the structure while subjecting it to no further distress.

In reinforced concrete structures, the status of the concrete and that of the reinforcing steel, both are equally important to determine the overall health of the structure. While evaluation of concrete health is easily feasible in non-destructive manner, the assessment of the reinforcement health poses more challenges. One of the methods would be through the application of empirical relationship between the resistivity of concrete to the corrosion current density and thereby indirectly evaluating the health of the reinforcing steel. Thus, concrete resistivity is being perceived as one of the most important parameters that can help to assess corrosion of steel in concrete. Generally, it is accepted that the corrosion rate decreases with increasing concrete resistivity under common environmental exposure conditions and such behaviour has been reported for concrete affected by chloride-induced corrosion as well.

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A comprehensive review of the various models available in literature has been provided by Hornbostel et al. [2]. They concluded that the scatter of corrosion current obtained from the various formulations have to be given due consideration while using the resistivity-corrosion current correlation. One of the limitations of the models available in literature was mentioned as the limited number of data used for developing the relationships.

Ahmad [3] proposed a relationship from 108 experimental results obtained from 10 specimens over different resistivity bands. The proposed relationship was compared with one reported by Gulikers [4]. Dauji et al. [5] proposed another empirical model and from different performance measures evaluated for the various models, they concluded that the model proposed by Dauji et al. [5] was superior to the models reported earlier. However, the proposed “Overall Power Model” underestimated for the corrosion current up to 2 μA / cm^2 while it overestimates beyond that value. This limitation is addressed in the present paper by dividing the entire domain into different ranges such that the estimations are balanced for the entire range.

2. Data and Methodology

2.1. Data

The experimental data reported by Ahmad [3] have been used in the study. Normal density concrete with reinforcement had been used for the tests. The design of the experiment is detailed in the literature [3].

2.2. Methodology

General relationship between the concrete resistivity and the corrosion current is reported in the following power form:

$$I = \frac{A}{R^B} \tag{1}$$

where I = corrosion current (μA / cm^2); R = concrete resistivity (kΩ.cm); A, B = empirical coefficients.

The values of A and B (Eq. 1) for the three models reported in literature are presented in Table 1.

Polynomial form of equation is also proposed in the following form:

$$I = A \times R^0 + B \times R^1 + C \times R^2 \tag{2}$$

As mentioned earlier, the model by Dauji et al. [5] underestimated for the corrosion current up to 2 μA / cm^2 while it overestimated beyond that value. Now, it appeared that the same set of coefficients for the entire range of resistivity was not suitable for giving the best performance. Hence, in this paper we employ the power relationship as well as the polynomial relationship and propose to give different sets of coefficients for different ranges of resistivity values.

Table 1: Coefficients for the empirical relationship between resistivity and corrosion current density [3- 5].

Model	Range of Resistivity (kΩ.cm)	Model coefficients (Eq. 1)	
		A	B
Simplified Gullikers [4]	-	15.39	0.8125
Ahmad [3]	0 – 65	18.84	1.3
Dauji et al. [5]	0 – 65	9.0757	0.8125

3. Results and Discussion

Henceforth, the models proposed in this paper shall be called as “Power Range (PR)” and "Polynomial Range (PnR)" respectively. The coefficients for the two models are presented in Table 2.

Table 2: Coefficients for the empirical relationship between resistivity and corrosion current density for proposed power range & polynomial range models.

Model	Range of Resistivity (kΩ.cm)	Form	Model coefficients		
			A	B	C
Power Range (PR)	0 – 5	Power (Eq. 1)	20	0.80	-
	5 – 25		12	0.80	-
	25 – 65		5	0.80	-
Polynomial Range (PnR)	0 – 5	Polynomial (Eq. 2)	10.0000	0.8000	-0.46000
	5 – 15		5.0100	-0.5900	0.02000
	15 – 25		1.4585	-0.0637	0.00062
	25 - 65		0.3000	-0.0040	0.00001

The performances of earlier models [3-5] are compared with those of the “Power Range” and "Polynomial Range" and the error measures are presented in Figures 1 to 5. It may be noted that dividing the domain into distinct ranges have improved the estimations as can be seen in correlation above 0.8 (Figure 1). The RMSE and MAE for the model-PR and model-PnR are also less than the Gulliker [4] and Ahmad [3] model (Figures 2 & 3). In the model-PR, the improvement in the correlation was accompanied with increase in the RMSE and MAE as compared to Dauji et al. [5] model. However, in the model-PnR, both these error measures are comparable to the Dauji et al. [5] model along with the highest correlation among the five (Figures 1, 2 & 3). Thus, the “Polynomial Range” (PnR) model appears to be the best among the five explored models.

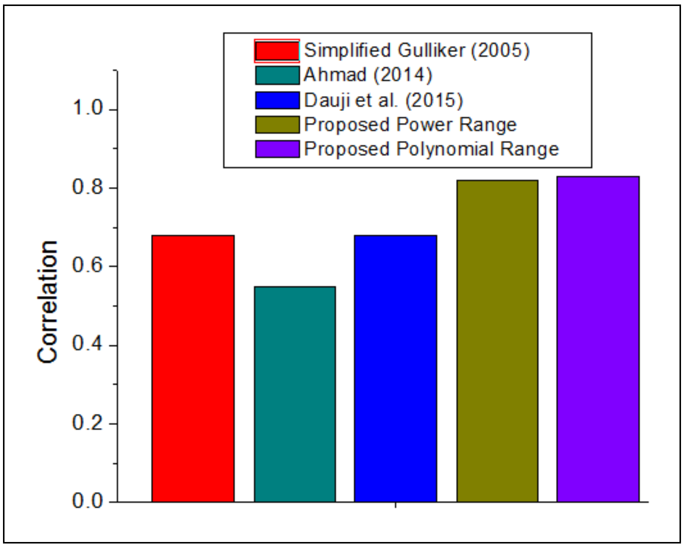

Figure 1: Correlation for the five models.

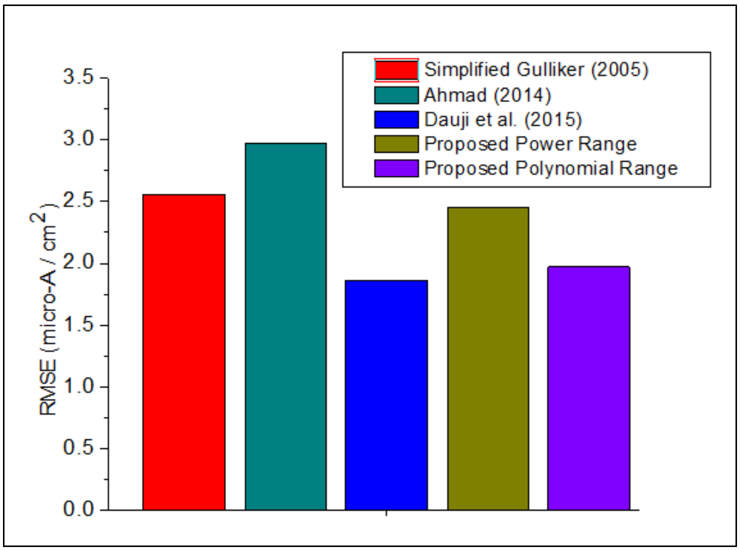

Figure 2: RMSE for the five models.

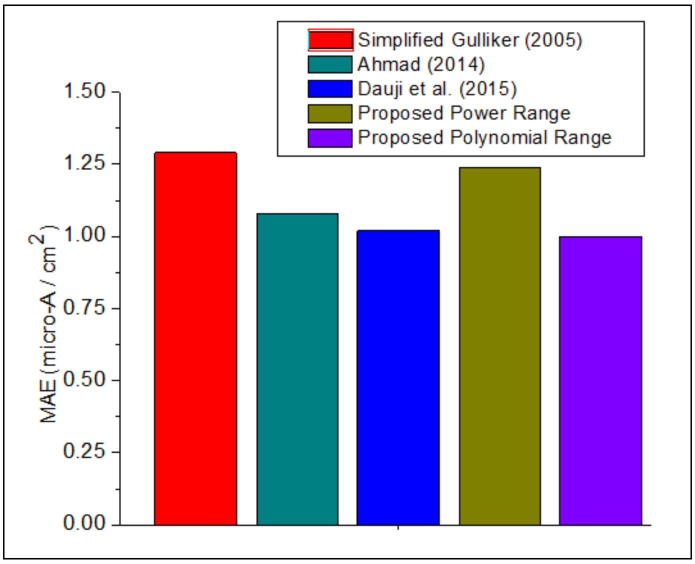

Figure 3: MAE for the five models.

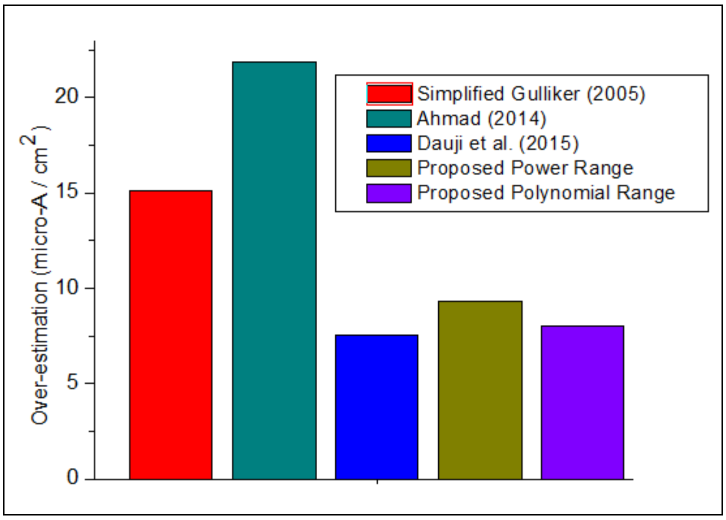

Figure 4: Overestimation for the five models.

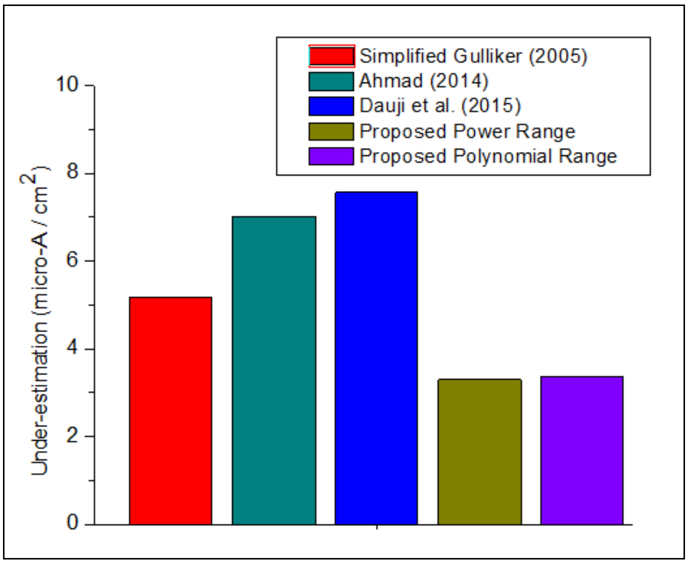

Figure 5: Underestimation of the five models.

When we consider overestimation, the model-PR gives slightly higher value as compared to the Dauji et al. [5] model though it is substantially less than Gulliker [4] or Ahmad [3] model. In case of model-PnR, the overestimation is the minimum, along with the Dauji et al. [5] model. From Figure 5, we can clearly notice that the model-PR and model-PnR yields the minimum values amongst the five models studied. Hence we conclude that the “Polynomial Range” gives the best empirical relationship for evaluation of the corrosion current density from the resistivity of concrete.

The observations and the model estimations are plotted in Figures 6 to 10 for the Simplified Gullikers model [4], Ahmad model [3], Dauji et al. model [5], and the proposed “Power Range” model & “Polynomial Range” model respectively. It is noted in that while the Gulliker [4] model (Figure 6) overestimates the corrosion current, the Ahmad [3] model underestimates it when resistivity is more than 5 k-ohm-cm (Figure 7). Ahmad [3] model further highly overestimates the model when resistivity is less than 2 k-ohm-cm. While Dauji et al. [5] model has balanced estimations till resistivity of 5 k-ohm-cm, beyond this value, the estimation is on the higher side (Figure 8).

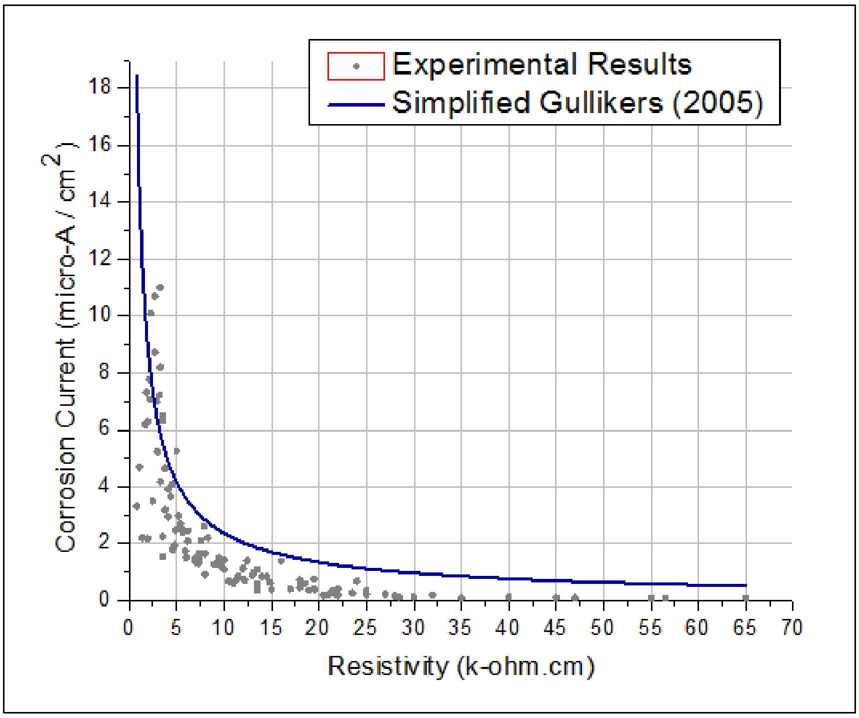

Figure 6: Comparison of experimental results and Gulliker's Model [4].

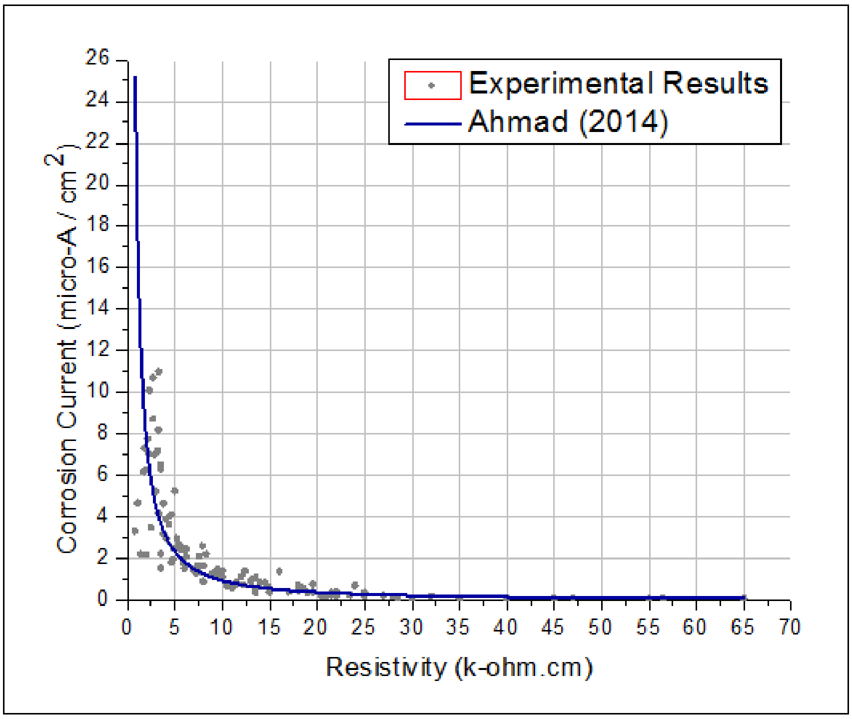

Figure 7: Comparison of experimental results and Ahmad's Model [3].

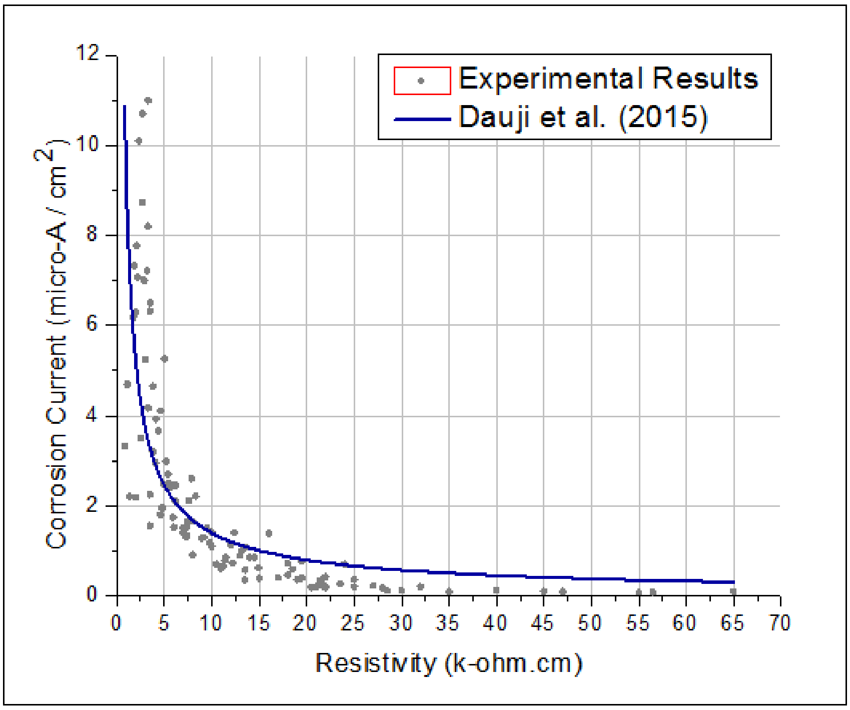

Figure 8: Comparison of experimental results and Dauji et al. Model [5].

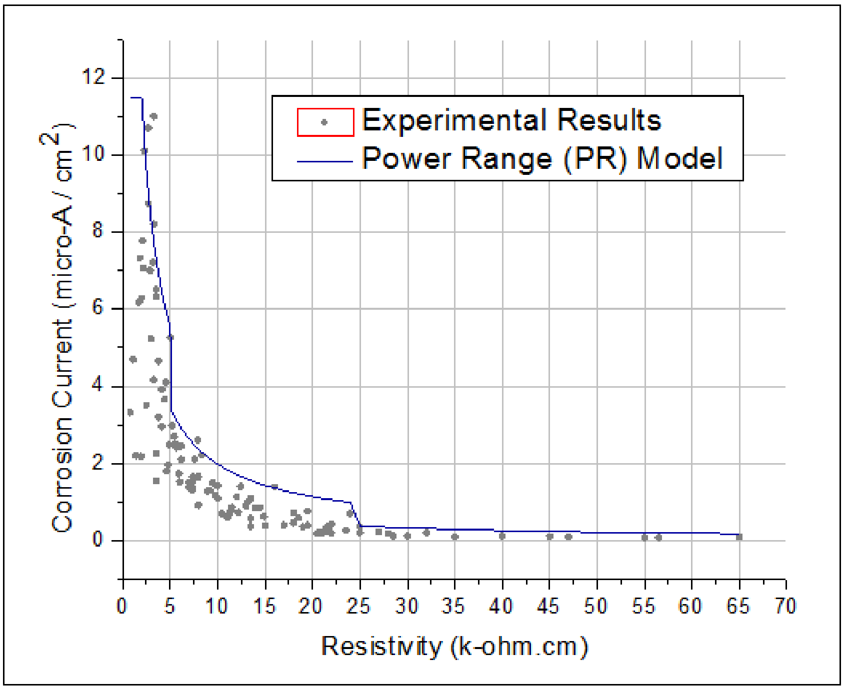

Figure 9: Comparison of experimental results and Power Range Model (proposed).

Looking at Figure 9, we may notice that though the performance metrics give a good feel, the estimations are apparently on the higher side for the PR model. In figure 10, we can clearly see that the PnR model closely follows the experimental values for the entire range and the estimations are balanced with the points falling equally on either side of the model. This corroborates our earlier finding that the "Polynomial Range" model bets fits the experimental data as compared to the other four models studied in this paper.

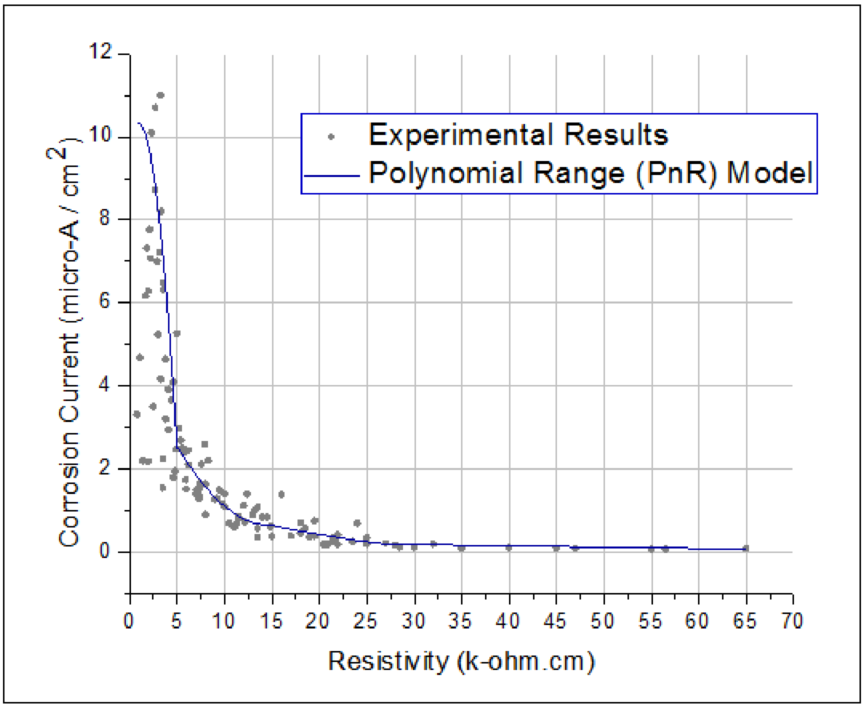

Figure 10: Comparison of experimental results and Polynomial Range Model (proposed).

4. Summary and Conclusions

From the present study, the following conclusions are drawn:

1. While Gulliker [4] model overestimates the corrosion current, the Ahmad [3] model underestimates it when resistivity is more than 5 k-ohm-cm.

2. Ahmad [3] model highly overestimates the model when resistivity is less than 2 k-ohm-cm.

3. Dauji et al. [5] model has balanced estimations till resistivity of 5 k-ohm-cm, beyond this value, the estimation is on the higher side.

4. For the proposed "Power Range" model, estimations are apparently on the higher side.

5. The proposed "Polynomial Range" model closely follows the experimental values for the entire range and the estimations are balanced with the points falling equally on either side of the model.

6. The "Polynomial Range" model has the highest correlation, and lowest or very near to lowest values of RMSE, MAE, overestimation and underestimation and thus is the best among the five models studied in terms of the performance measures.

Future work would be directed towards achieving better correlation and lowering the over/under estimations while estimating the corrosion current indirectly from resistivity measurements of concrete by advanced techniques.

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