CORROSION-DEGRADATION PREDICTION OF STEEL BRIDGE PAINTINGS

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ABSTRACT This study performed accelerated exposure tests on five types of painting systems, which are the most common painting systems for steel bridges in Japan, and discussed corrosion degradation from initial defects on the paintings. Structural steel plates were surface-treated and painted conforming to the Japanese Painting Manual, and circular defects of 0.2 mm, 1.0 mm, and 2.0 mm diameters reaching the steel substrate were created. The painted steels were exposed into an environmental test chamber controlled by the S6-cycle test condition (Japanese Industrial Standards (JIS) K5600) for up to 600 days. Corrosion degradation of the each painting was evaluated based on rusting area from the circular defects, which was measured by using Laser Focus Measuring Instrument at 250 μm intervals. The proposed degradation curves were applied to remaining lifetime evaluation for the painted steels with initial defects to the future conditions.

KEYWORDS: Steel bridge, Painting, Corrosion-degradation, Accelerated corrosion test, rust propagation

1. INTRODUCTION

Painting has been widely used to prevent corrosion attacks, to maintain the functional ability and to keep good appearance of steel bridges. Sound paintings protect the steel substrate and limit ingress of water and oxygen. When the paintings age and degrade, the rate of infiltration increase, and eventually the performance is degraded exponentially.

In Japan the painting area of the steel bridge is about 40 million m^2 and about 8 % of them is repainted these every year [1]. Moreover, the predicted repainting area and cost keep increasing every year according to increase in steel bridge asset. The remaining lifetime prediction of painting films is important to maintain steel bridges efficiently.

The performance of steel bridge paintings were often examined by bridge inspection, and the aged degree of painted members was ranked by using the coating manual or the standard test methods, such as JH [2], JSSC [3], JIS [4], JRA [5] and ASTM [6]. For example, degradation grade of the current paintings can be evaluated by comparing it with the visual examples depicting the rusting area percentage in the standards [4] - [6]. Field exposure test at a known site is a method for performance assessment of bridge paintings. Measuring glossiness, tensile adhesion or rust rate on painted specimens in long-term exposure time gives a degradation plot for them [7], [8]. Although the bridge inspection and the exposure tests allow field examinations, it takes long time to obtain any degradation data of the paintings. It is difficult to evaluate the remaining lifetime of bridge coating systems at the stage of the bridge inspection and the performance of newly developed painting systems in a short time. This can give rise that maintenance requirements tend to become urgent and are usually constrained by an inadequately prepared budget.

In this study accelerated exposure tests, which is employed to obtain the fundamental data for corrosion behavior in a short time and to complement the data of the field exposure tests, were carried out on five types of steel bridge paintings. Based on the rusting area from the initial defects on the painted specimens, corrosion degradation is discussed. The application of the proposed degradation curves to remaining lifetime evaluation is also presented.

2. TEST PROCEDURE

2.1 TEST SPECIMENS

Figure 1 illustrates the geometry and dimensions of the test specimen used in this study. The steel plates of 150 mm long, 70 mm wide and 9 mm thick were cut from Japan Industrial Standards (JIS) SM490A structural steels [9]. The steel plates were grit-blasted by No.50 grit specified in JIS S-G50 or surface-treated by a power tool machine, which is a common surface treatment prior to steel bridge painting in Japan. And the steel plates were coated with five types of painting systems, which are named A-painting system applied for mild condition and C- and I- painting systems for severe corrosive condition in Japan [4]. For recently developed I-painting systems three types with different top coats was prepared, and was named I1-, I2- and I3-painting systems in this study. The coating materials and process are listed in **Table 2**.

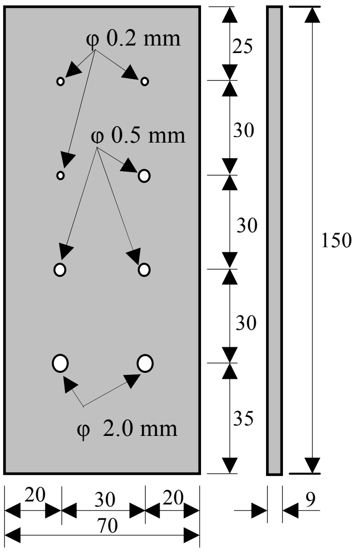


Fig. 1 Test specimens (units in mm)

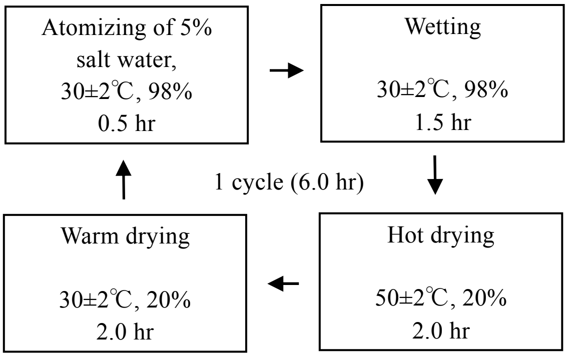


Fig. 2 S6-cycle test condition

Table 2 Coating systems used in this study

Symbol of test specimens	Painting process	Treatment and material	Designed film thickness (μm)
A-painted steel	Surface preparation	Power tool, SIS-St3 Class	-
	1st Undercoat	Lead anticorrosive paint	35
	2nd Undercoat	Lead anticorrosive paint	35
	Intermediate coat	Alkyd resin	30
	Top coat	Alkyd resin	25
C-painted steel	Surface preparation	Blast, SIS-Sa2 1/2 Class	-
	1st Undercoat	Inorganic zinc-rich paint	75
	-	Mist coat	-
	2nd Undercoat	Epoxy resin	60
	3rd Undercoat	Epoxy resin	60
	Intermediate coat	Polyurethane resin	30
	Top coat	Polyurethane resin	25
I1-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	-
	Undercoat	Organic zinc-rich paint	75
	Intermediate coat	Polyurethane resin	30
	Top coat	Polyurethane resin	25
I2-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	-
	Undercoat	Organic zinc-rich paint	75
	Intermediate coat	Silicone acrylic resin coating	30
	Top coat	Silicone acrylic resin coating	25
I3-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	-
	Undercoat	Organic zinc-rich coating	75
	Intermediate coat	Fluorine resin	30
	Top coat	Fluorine resin	25

As shown in **Fig. 1**, circular defects of 0.2 mm, 1.0 mm and 2.0 mm diameters reaching the steel substrate were created in the each painted specimen with an automatic milling machine. In the following φ 0.2 mm, φ 1.0 mm and φ 2.0 mm defects is named D-0.2, D-1.0

and D-2.0 defects, respectively. Total eight circular defects, three D-0.2, three D-1.0 and two D-2.0 defects, were introduced into each test specimen. Two specimens for each painting systems were prepared. Two A-painted specimens without the defects were also prepared for comparison.

In the evaluation of performance of coating films, a scribe line or its combination are mainly used, and distance between the center of the scribe and minimum, mean or maximum edge of blistering or visible rust creepage was used in degradation evaluation. In this study scribe circle was selected as the defect shapes, based on the reasons; the rusted shape on painted main member of steel bridge is similar to a circle rather than a line and rusting area represented in graphic standards (ASTM D610) for evaluation of rust grade or rust rating closes to circle.

2.2 TEST INSTRUMENT AND CONDITIONS

A combined cyclic corrosion test instrument (Casser-20L-CYH) [10], which can operate automatically the conditions of atomizing of salt water, temperature, and humidity in arbitrary order and combination, was used to simulate corrosive environments. This equipment has an environmental test chamber of 2000 mm long, 1000 mm wide and 500 mm high in which 188 test specimens of 70 mm × 150 mm can be arranged in maximum. The environmental condition of the chamber was controlled conforming to the S6-cycle test condition, which consist of 30 minutes of slat water atomizing, 90 minutes of wetting, 120 minutes of drying by hot wind, and 120 minutes of drying by warm wind, as shown in **Fig. 2**.

The S6-cycle test is specified as an accelerated exposure testing method for anticorrosive paintings in JIS K5600. The reproducibility of the S6-cycle test for degradation grades of painted steels under field environments was presented in literatures of Fujiwara [8] and Saito [11]. With the comparison of 7 types of accelerated exposure tests in laboratory and field exposure tests at 4 sites in Japan, Fujiwara [8] proposed that the S6-cycle corrosion test gave the good correlation with outdoor exposure tests, among the accelerated exposure tests. Saito [11] also presented the reproducibility with 4 types of accelerated exposure tests and field exposure tests at 3 sites in Japan.

2.3 TEST PROCEDURE AND MEASUREMENT

All prepared test specimens were placed at an angle of 15° from the vertical in the chamber, and exposed for up to 600 days. Every 25 days visual inspection was performed on the specimens, and every 100 days the specimens were taken out from the chamber and blotted the surface with a wet tissue to remove any attachments. And we taken photographs of the appearance and measured the surface geometry of the specimens. In the measurement the Laser Focus Measuring Systems consisting of an automatically X-Y moving stage with minimum moving interval of 1 μm, the laser distance meter of reading precision of 1μm and automatic measuring and recording systems, was used. Every 100 days using the tests the 150 mm-long and 70 mm-wide surface with the initial defects was measured at 250 μm intervals, and relative height measured by the laser distance meter was recorded for 168 thousand points.

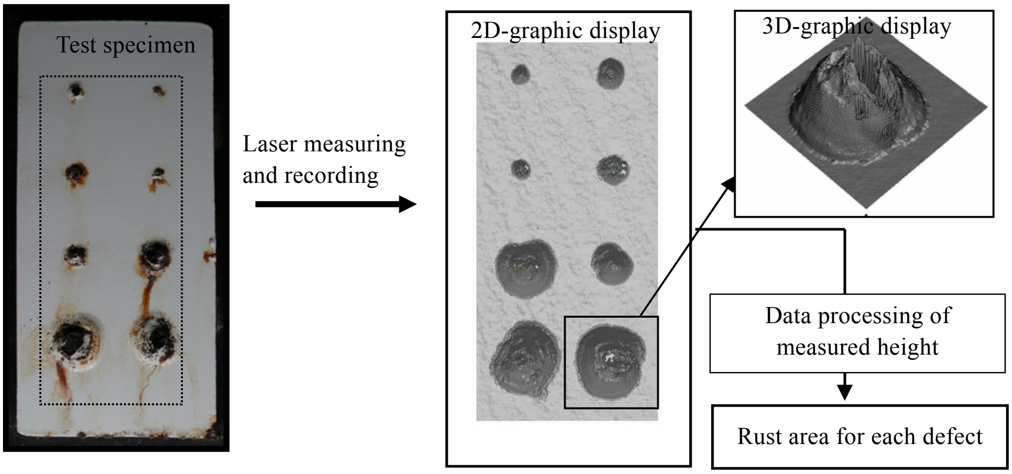


Fig. 3 Calculation of rusting area

Figure 3 shows the calculation process of rusting area around the each defect. Prior to exposure testing, the geometry of painted surfaces far away the initial defects, which is named base surface in the following was measured by the laser measuring system, it was confirmed that maximum roughness of the painted surface was less than 50 μm. Considering the maximum roughness the measuring points having 50 μm heights more than the base surface was taken as rusting points, and the rusting area around the each defect was calculated. In the early stage of testing the laser measurement was also carried out between the predetermined intervals of 100 days.

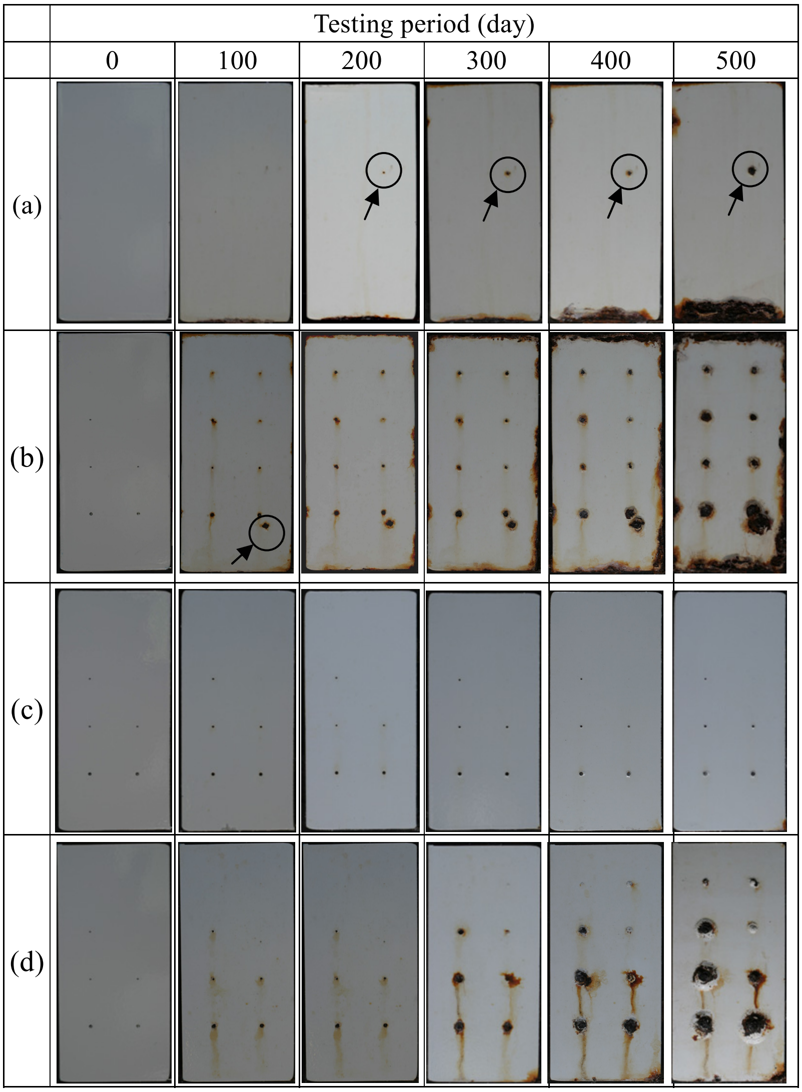
3. EXPERIMENTAL RESULTS

3.1 MEACHANISM OF RUST PROPAGATION FROM A SCRIBE ON PAINTING

The mechanism of rust propagation from a circular scribe on painted steels with an initial defect was presented by Funke [12], Reddy [13], [14] and Doherty [15]. They empirically examined rust propagation from the scribe beneath painting films using the scanning Kelvin probe or scanning acoustic microscopy, and presented that potential reversal of anode and cathode at the scribe, beneath the painting films and the advancing edge results in coating failure and underfilm rust propagation. Rust propagation procedure from the initial defects on the painted specimens used in this study can be also explained by the mechanism.

Fig. 4 Appearance change in the painted specimens

(a) A-painting without defects (b) A-painting (c) C-painting (d) I1-painting



3.2 VISUAL INSPECTION

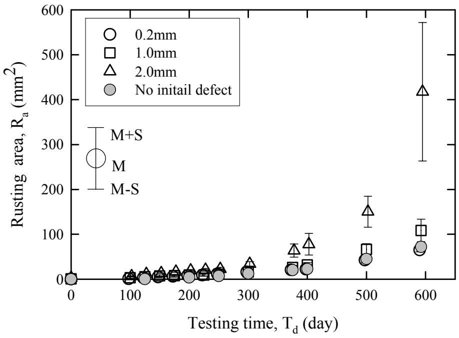
Typical surfaces of A-, C- and I1-painted specimens every 100 cycles are shown in **Fig. 4.** In the painted specimens with the initial defects, rust originated at the defects, filled up them, undercut the paint film/steel substrate interface, and spread beneath the painting films around the defects. Testing time until the defect was plugged with rusts is about 25 days on the A- and I-painted specimens and about 50 days on the C-painted specimens. According to rust propagation beneath the paintings, the area of rust creepage or blistering of A- and I-painting films was widened far away from the each defect, as shown in the **Fig. 4(b) and (d)**. On the other hand, rust propagation on C-painted specimens was invisible by naked eyes, as shown in **Fig. 4(c)**.

From the test specimens, rust initiation and propagation were observed only from the initial defects. In case of an A-painted specimen, a scratch near a D-2.0 defect was created by mistake in spite of all careful treatment of the test specimens, and rust at the scratch was formed, as shown in **Fig. 4(b)**. The rusting area from the scratch is not to be considered in rusting area evaluation. For one of the two A-painted specimens without the initial defects, a dot-rust was originated from a point at 125 days and it propagated with testing time, as shown in **Fig. 4(a)**.

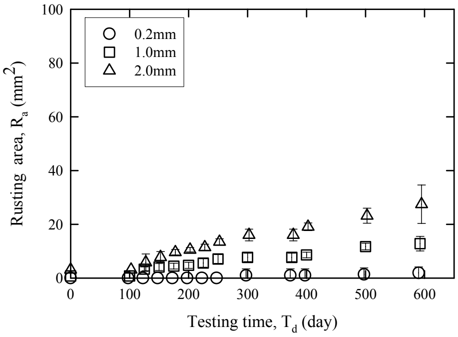
3.3 RUST PROGATION FROM EACH DEFECT

Mean (M) and standard deviation (S) of the measured rusting areas from φ 0.2 mm (D-0.2), φ 1.0 mm (D-1.0) and φ 2.0 mm (D-2.0) defects are plotted against to the testing period in **Fig. 5**. As shown in **Fig. 5(a)**, each rusting area on the A-painted specimen increases lineally until testing period reaches 300 days, and then increases rapidly. Rusting areas for the all I-painted specimens show the similar increase to those for the A-painted specimens, as shown in **Figs. 5(c)**. For the C-painted specimen no increases in rusting area from D-0.2, D-1.0 and D-2.0 defects was measured when the testing time reached 250 days, 100 days and 100 days, respectively and tend to increase lineally after that.

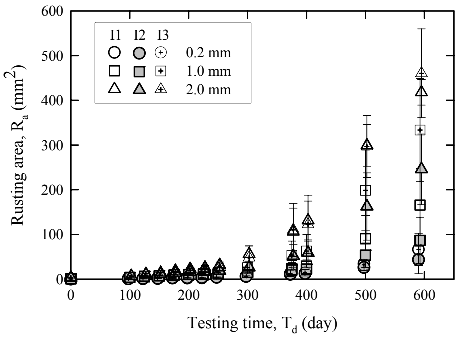
In the **Fig. 5(a)**, rusting area of the A-painted specimen without initial defects was shown. The rusting area from a dot-rust is approximately equal to the mean rusting area of the D-0.2 defects. From the comparison of the rusting area of the A-, I- and C-painted specimen it was observed that the rusting area increases in the order of the I3-, A-, I1-, I2- and C-painted specimens, even though the difference between the I3-, A- and I2-painted specimens is little. In case of the I-painted specimens with different top paints the rusting areas increased in order of the measured painting thickness prior to testing. It indicates that the thickness of painting films affects the rusting area and rust propagation.



(a) A-painted specimen

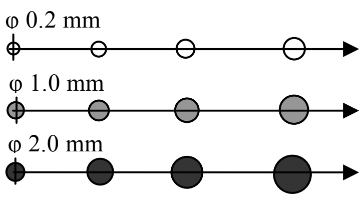


(b) C-painted specimen

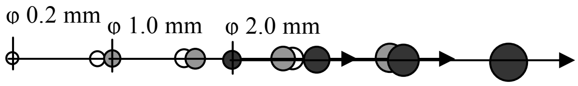


(c) I-painted specimen

Fig. 5 Rusting areas of each specimen



(a) Each rusting area



(b) Combined rusting area

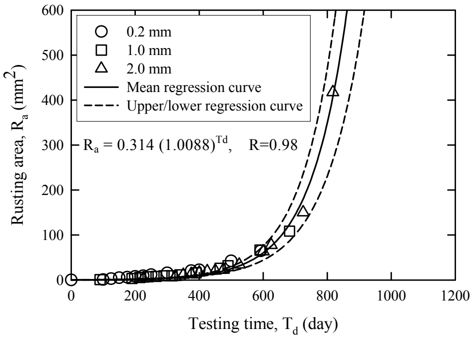
Fig.6 Combination of the measured rusting areas

3.4 DETERMINING DEGRADATION CURVES FOR EACH PAINTED SPECIMEN

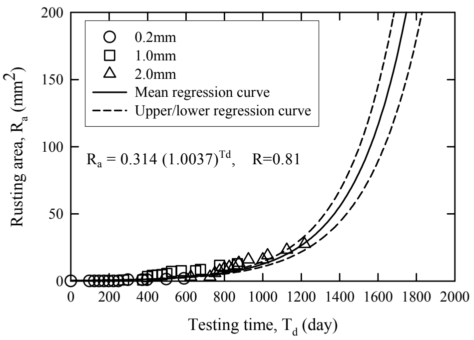
Although the measured rusting area represented only one stage along the rust propagation process from D-0.2, D-1.0 and D-2.0 defects, gathering the data enabled us to reconstruct the rust propagation the overall procedure. If the testing time until rusting area of 0.2 mm diameter (D-0.2 defect) reaches the 1.0 mm (D-1.0 defect) and 2.0 mm diameter (D-2.0 defect) was determined, all measured rusting areas from the D-0.2, D-1.0 and D-2.0 defects can be expressed with only those from D-0.2 defect, as shown in **Fig. 6**. This combination gives that the rust propagation curve from the D-0.2 defect can be determined with the higher reliability than only considering D-0.2 defect and extended to the long testing time based on the test data.

In this study, the rust propagation time from D-0.2 defect to D-1.0 and D-2.0 defect was determined from the rust propagation curve of the D-0.2 defect. The required testing times are respectively 75 and 200 days for the A-painted specimen, 275 and 625 days for C-painted specimen, 125 and 225 days for I-painted specimens. Considering these testing times, the rusting areas from the defects was rearranged by the shifted testing time, as shown in **Fig. 6**. In addition to this, the testing time was shifted by 25 days for A- and I-painted specimens and by 50 days for C-painted specimen, which are the elapsed time from rust initiation at the defects to rust filling up them, as the previous description.

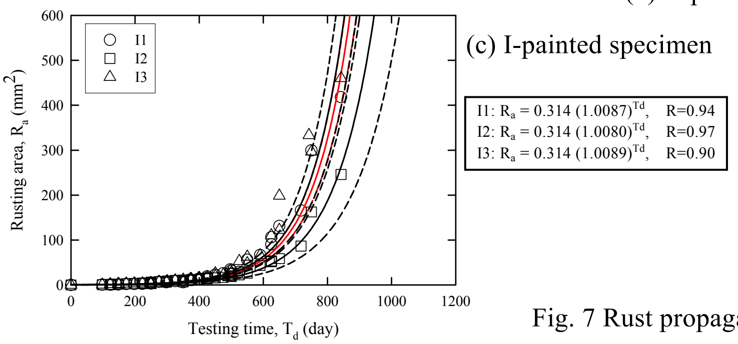
The rust propagation curves for each painted specimens are shown in **Fig. 7**. The mean regression curves ($y = ab^x$, where a and b are constant) obtained by the least squares method are also plotted. The upper and lower regression curves, located a standard deviation far away from the mean regression curve, are plotted by dotted lines. In calculating the regression curves, the constant a is fixed as 0.314 showing the higher correlation coefficient for all data. **Figure 7** indicates that the rusting areas from the three different defects, D-0.1, D-1.0 and D-2.0 defects, can be rearranged by the above procedure and be expressed by the mean regression curve with high correlation coefficient R of over 0.81.



(a) A-painted specimen



(b) C-painted specimen



(c) I-painted specimen

Fig. 7 Rust propagation

Using the regression curves, rust propagation rate at a testing time and the remaining testing time of a defect to the future condition for the A-, C- and I-paintings can be evaluated as the defect is more than 0.2 mm diameter. It is also applicable to multiple defects with different sizes on the painting by summation of rusting areas for each defect.

Remembering that rust initiation and propagation on the A-painted specimens without the initial defects was observe and the rusting area was almost equal to that the D-0.2 defect on the A-painted specimen, the rust initiation time to 0.2 mm diameter may be neglected in the A-painted specimen. In case of the A-painted specimens, therefore, the rust propagation curve is applicable to degradation prediction for sound A-painted steels.

5. SUMMARY

In order to determine rust degradation curves for steel bridge paintings, this study carried out accelerated S6-cyclic corrosion tests on painted steels with five types of steel bridge painting systems during 600 days. Based on rusting area from initial defects with 0.2 mm, 1.0 mm and 2.0 mm diameters, rust degradation curves for each painting systems was presented. And the application of the degradation curves for remaining lifetime evaluation from one to another degradation grade was also presented.

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