- Technical Paper -

DETERMINATION OF YOUNG`S MODULUS OF RUST-LAYER BY BENDING EXPERIMENT

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ABSTRACT

A new experimental method for evaluating Young's modulus of rust layer has been proposed by simply-supported 4-point bending tests. Difference of flexural rigidities between two steel plate beams with and without corrosion upon is supposed to present the mechanical properties of rust layer. Among them, the initial tangent Young's modulus of rust layer obtained from 18 specimens concluded the possible range of several GPa. This method has manifested itself not only simple but more reliable by performing on the real rust above virgin steel.

Keywords: rust layer, Young's modulus, composite beam, flexural rigidity

1. INTRODUCTION

1.1 Context of the study

Cracking in concrete structure due to the corrosion of reinforcement steel is one of the major factors inducing degradation of its durability and even premature failure. In order to evaluate the residual serviceability and ultimate capacity in such structures based on numerical modeling, the mechanical behavior of corrosion product (i.e., rust) at the interface between corroded steel and concrete must be known. Since the splitting stress in concrete cover is resulted from the volume expansion of rust and the corresponding deformation restriction of concrete around, most studies focus on the Young's modulus of rust (E_r) along with a few on its stress-strain relationships. A brief review upon relevant literatures among them is listed in Table 1.

Table 1 Literatures review

Authors	Methods	Results
Lundgren[1]	Corrosion cracking tests and FEM analyses.	stress-strain relation ($t_n = 14\varepsilon_{cor}^7$) E_r ≈0.3GPa
Ouglova[2]	Oedometer test and Ultrasonic measurements	E_r= several GPa
S.Care[3]	Corrosion cracking tests through digital image correlation with analytical model	E_r ≈0.13GPa
A.Dehoux[4]	Micro-indentation tests	E_r =50-200GPa
Yuxi Zhao[5]	Compression test and oedometer test	E_r =0.1GPa

So far, the experimental studies can be classified into three categories, consisting of corrosion cracking tests[1,3], corrosion product tests[2,5] and indentation tests[4]. In case of cracking tests, Young's modulus of rust is obtained based on the combination of experimental data with theoretical analyses. Such as in the study of [1], Lundgren et al obtained the relationship of normal stress versus strain in the rust (Fig.1) based on axisymmetric finite element analyses

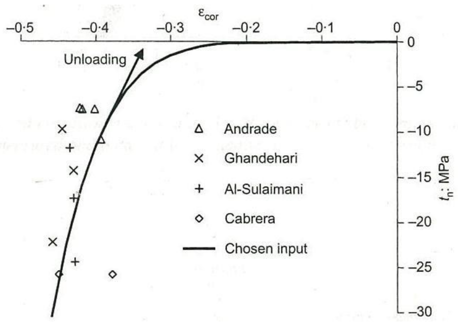

Fig. 1 Normal stress versus strain of rust[1]
(Note: E is obtained by the unloading tangential)

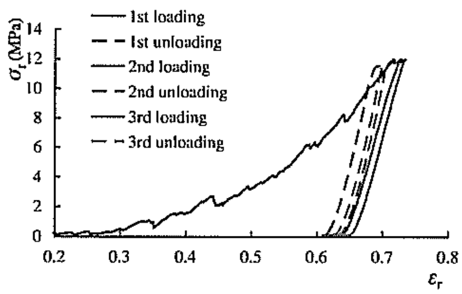

Fig.2 Stress-strain curve by low-compression test[5]
(Note: E is obtained by the unloading tangential)

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of a concrete cylinder and related deformation of rust collected from several corrosion cracking tests. The estimated E_r from the unloading line is around 0.3GPa. S. Care et al[3]used digital image correlation for displacement field measurements and substituted the experimental data into an analytical model (hollow cylinder subjected to inner and outer pressures) for estimation of the order of magnitude of Young's modulus of rust layer. Obviously, this experimental category cannot escape the effects of specific specimen such as concrete/mortar properties, cover thickness and corrosion situation like rust layer thickness et al. Additionally, in the process of analyses, several assumptions are necessary including expansion coefficient and Poisson's ratio of corrosion product, and no rust filling into the pores.

In case of corrosion product tests, rust samples collected from the site in different environment are peeled from the steel specimen previously. Loading tests are mostly performed through oedometer test, a common method for testing soil in the field of geo-mechanics. Besides, Ouglova[2] et al also perform the ultrasonic measurements during oedometer testing and got consistent values. Yuxi Zhao[5] et al performed low-compression tests (Fig.2) by putting rust flakes directly on the tray of universal tester in addition to oedometer tests. A value of 0.1GPa is suggested for E_r. A major problem in this category is that original configuration of rust lay has been interfered by removing it from the virgin steel, leading to wonder whether the results may represent the real situation.

Granted, in case of indentation tests, the measurement is performed on the original rust layer above steel without any interference. However, the obtained mechanical properties are at its micrometric scale, solely representing the local circumstances. A value as large as 200MPa has been reached for E_r.

Upon above brief literature review, the obtained Young's modulus of rust are found to be in a large range from 0.1GPa to 200GPa. The largest values occurred in indentation tests is even approximately equivalent to steel's Young's modulus. It shows that local properties are totally the other way around against the whole picture of rust shown in other experiments. Smaller values of several GPa is seemingly reasonable, but need to be proved further as to its availability in general circumstance by some general way.

1.2 Aims

The aim of our study is to explore a sort of general experimental method for testing Young's module of rust layer at its original configuration on the virgin steel, without any other possible influential factors and un-avoidable sophisticated testing techniques.

A new experimental method of simply-supported four-point bending composite beam is presented for obtaining mechanical features of rust layer. It is because a steel plate beam with uniform rust layer above physically constitutes a kind of composite beam. By comparing the different flexural rigidity between this corroded composite beam and its corresponding un-corroded one, we may attain the Young's modulus of rust layer on the top of the steel beam.

Obviously, it is not only a much simpler but also more reasonable way than those in literatures because (1) the rust layer may keep its original configuration in the midst of testing; (2) steel sample is not necessary to be embedded into concrete/mortar specimen, surely eliminating related influential factors in corrosion cracking tests mentioned in section 1.1;(3) four-point loading of simply-supported beam is a commonly classical mechanics test.

Before going forward, two questions need to be explained: (1) the rust-layer upon steel plate may not be the same as that upon steel within concrete because of different environmental conditions; (2) the corrosion product generated within concrete is grown up under compressive restraint through concrete cover while rust-layer upon steel plate is not.

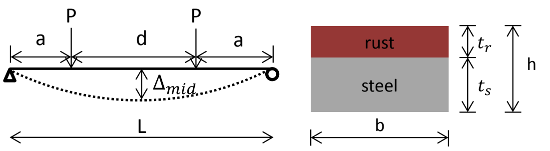
Referring to question (1), the chemical components of rust are determined by environment condition mainly including content of water and oxygen, and pH-value. Based on Table 4 of the study [6], corrosion product generated upon steel in air shows mostly the same components consisting of Goethite ($\alpha-\mathrm{FeOOH}$), Akaganeite ($\beta-\mathrm{FeOOH}$), Lepidocrocite($\gamma-\mathrm{FeOOH}$) and Magnetite(Fe_3O_4) as that upon steel within concrete, except $CaFeO_2Cl$ existing in case of steel within concrete. In section 3.1 below, XRD chart analysis of the steel plates in this paper also prove the similar result. Because the components of rust may be generated by controlling the required conditions [6], rust layer in various environments could be purposely produced upon steel plate for mechanical experiments. However, these influential factors will not be taken into account at this moment.

Referring to question (2), the restraint coming from concrete cover is exactly the external compressive force acted upon the rust in the process of its growth and definitely the reason why rust-layer is laid on the compressive side of the plate in bending experiment.

Additionally, the volumetric expansion ratios of rust produced within concrete and freely in air have been found to be approximately close each other (Table 11 in [6]). So, the restraint force by concrete cover has no huge influence on the corrosion products.

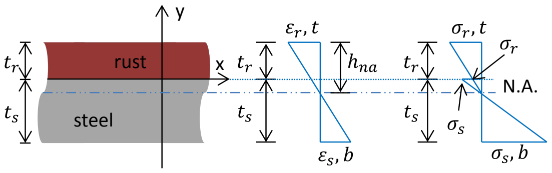
Above all, the study is to testify the feasibility and availability of 4-point bending tests for determining Young's module of rust layer in compression.

2. PHYSICAL MODEL OF CORRODED STEEL PLATE- BEAM SUBJECTED TO 4-POINT BENDING



(a) (b)

Fig. 3 Corroded steel plate beam under 4-point bending loads



(a) (b)

Fig.4 Stress and strain distribution along the cross-section

It has been observed that rust on steel is a layer of oxides in the form of laminated stratums [2]. Therein, as long as the rust layer upon steel plate is uniform and thick enough relative to its substrate un-corroded-part steel, the corroded steel plate may be considered as a composite plate beam consisting of two materials, rust layer and virgin steel. The physical model of a simply-supported corroded steel plate beam under 4-point bending load illustrated in Fig.3 shows the basic image of the experimental scenario. The rust layer is purposely put at the upper side of the beam because its compressive properties are of interest.

Bernoulli-Euler hypothesis is assumed to be followed as shown in Fig.4(b), because the loading is within elastic range and rust-layer is completely bonded with steel plate by growing upon it without any interruption. Based on elastic bending theory, the mid-span deflection of the beam shown in Fig.3a can be expressed respectively for the corroded composite beam and its un-corroded part steel beam as:

$$\Delta_{mid,com}=\frac{Pa}{24(EI)_{com}}(3L^2-4a^2) \quad (1)$$

$$\Delta_{mid,unc}=\frac{Pa}{24E_sI_{s,unc}}(3L^2-4a^2) \quad (2)$$

Recall that all the cross-sectional properties should be given relative to its neutral axis h_{na} (Fig.4a) in case of composite beam, the inertia of moment of rust layer and steel substrate in Eq.1 may be expressed as follows:

$$I_r=\frac{1}{12}bt_r^3+bt_r(h_{na}-\frac{t_r}{2})^2 \quad (3)$$

$$I_s=\frac{1}{12}bt_s^3+bt_s(h-h_{na}-\frac{t_s}{2})^2 \quad (4)$$

Flexural rigidity of composite corroded beam is thereby to be the rigidity sum of rust layer and un-corroded steel:

$$(\mathrm{EI})_{com}=E_rI_r+E_sI_s \quad (5)$$

As far as the location of neutral axis, it may be obtained according to the force equilibrium equation $\sum F_x=0$ in x direction along cross section (Fig.4b), leading to

$$\int_{rust}\sigma_r dA+\int_{steel}\sigma_s dA=0 \quad (6)$$

Applying Hooke's law to two materials and by using of $\varepsilon=\kappa y$, it becomes:

$$E_r\int_{rust}ydA+E_s\int_s ydA=0 \quad (7)$$

The position of neutral axis may be derived by:

$$h_{na}=\frac{t_r^2/_2+n(t_rt_s+t_s^2/_2)}{t_r+nt_s} \quad (8)$$

In case of the un-corroded part, only a single material exists. The moment of inertia is:

$$I_{s,unc}=\frac{1}{12}bt_s^3 \quad (9)$$

The symbols involved in above equations are listed below:

κ: the curvature of the beam
t_r: thickness of rust layer
t_s: thickness of un-corroded steel plate
b: width of cross section of the beam
h: height of cross section of the beam
h_{na}: distance of neutral axis away from the top of composite beam of two materials including rust layer and un-corroded steel part.
I_r: moment of inertia of rust layer with respect to the N.A. of the composite beam
I_s: moment of inertia of un-corroded steel part with respect to the N.A. of the composite beam
$I_{s,unc}$: moment of inertia of un-corroded steel part with respect to the N.A. of its own part
E_s: Young's module of steel
E_r: Young's module of rust
n: ratio of Young' modules of steel to rust, $n=\frac{E_s}{E_r}$
$(\mathrm{EI})_{com}$: the flexural rigidity of the composite beam
L: span of the beam
a: the loading position of four-point bending determined by the accuracy degree of the experiment apparatus.
$\Delta_{mid,unc}$: the mid-span deflection of beam with un-corroded steel part alone
$\Delta_{mid,com}$: the mid-span deflection of composite beam with two materials including rust layer and un-corroded steel part.

Dividing Eq. 2 by Eq.1, the rigidity ratio of two beams can be produced by the ratio of the corresponding mid-span deflections by:

$$\frac{\Delta_{mid,unc}}{\Delta_{mid,com}}=\frac{(EI)_{com}}{E_sI_{s,unc}}=\frac{E_rI_r+E_sI_s}{E_sI_{s,unc}}=\frac{I_r+nI_s}{nI_{s,unc}} \quad (10)$$

Given the thicknesses of rust layer and un-corroded part, it is seen that the rigidity ratio is an explicit function in n alone. Then, E_r may be determined by E_s/n. It should note that E_r in this paper refers to the initial tangent Young's modulus because the prerequisite of the above derivation is both rust layer and steel in the composite beam are within elastic range.

3. EXPERIMENTAL PROGRAM

3.1 Specimen preparation and the characterization of corrosion product

Two groups of steel-plates specimen (Table 2) are selected with the same span of 100mm and width of 20mm, except for varying the thickness to 1mm (specimen No.1.0-1~1.0-9) and 1.6mm(specimen No.1.6-1~1.6-9) respectively. Salt-spraying on one surface of steel plate was carried out in constant temperature room (20℃ , 61% RH). Uniform rust-layer thickness was observed and testified by infra-red vision in the midst of corrosion process. XRD patterns (Fig.5) for rust peeled from arbitrarily selected 3 specimens show almost the same components mainly of Magnetite and Goethite, leading to the assumption that corrosion product components would not be considered as an influential factor on mechanical behaviors of steel plate in later analyses. Photo 1 shows the image of the corroded steel plate specimen.

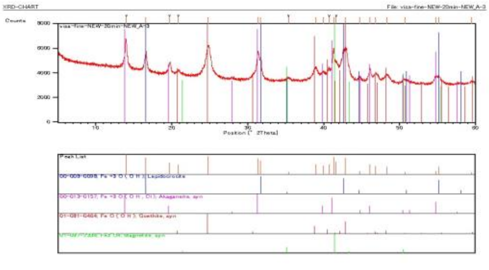


Fig. 5 XRD patterns of rust-layer on steel plate

Photo 1 Corroded steel plate specimen

3.2 Measurement of thicknesses

Due to corrosion, the thickness of steel plate (t_s, the un-corroded part) became less than its original thickness h (1mm or 1.6mm), while the total height of the corroded specimen increased to h_{com} (sum of t_s and t_r). Caliper ruler with accuracy to 0.05mm is used for measurement of h_{com} and the average thickness is adopted from collected values at 5 different positions 20mm apart along the 100mm-span. Average rust-layer thickness t_s is calculated by dividing the remaining steel plate weight after cleaning the rust over steel density of 7.8 g/cm^3.

As listed in Table 2, in case of specimen with original thickness of 1.00mm, h_{com} is approximately 1.79mm on average (of 9 specimens) covering t_s of 0.83mm and t_r of 0.96mm; In case of specimen with original thickness of 1.6mm, h_{com} is approximately 2.41mm on average (of 9 specimens) covering t_s of 1.33mm and t_r of 1.08mm. Rust layers are therefore thick enough as against the remaining steel plate ($t_r/t_s \approx 1$) to establish a second material layer for corroded composite beam. Also, the five locations for measuring thickness in all specimens give almost the same result as expected.

Table 2 testing results for 18 specimens

Specimen No.	h_{com} (mm)	t_s (mm)	t_r (mm)	$EI/E_s I_{s,unc}$	n	E_r (GPa)
1.0-1	1.70	0.82	0.88	1.49	29	7
1.0-2	2.00	0.82	1.18	1.54	50	4
1.0-3	1.80	0.83	0.97	1.36	50	4
1.0-4	1.65	0.82	0.83	1.40	35	6
1.0-5	1.70	0.83	0.87	1.39	35	6
1.0-6	1.90	0.84	1.06	1.29	70	3
1.0-7	1.75	0.84	0.91	1.33	45	5
1.0-8	1.80	0.83	0.97	1.34	33	6
1.0-9	1.80	0.81	0.99	1.31	50	4
1.6-1	2.45	1.33	1.12	1.18	50	4
1.6-2	2.45	1.36	1.09	1.35	23	9
1.6-3	2.35	1.34	1.01	1.22	35	6
1.6-4	2.40	1.32	1.08	1.05	150	1
1.6-5	2.40	1.29	1.11	1.09	100	2
1.6-6	2.25	1.34	0.91	1.23	25	8
1.6-7	2.60	1.34	1.26	1.33	35	6
1.6-8	2.40	1.37	1.03	1.21	35	6
1.6-9	2.40	1.32	1.08	1.16	150	1

3.3 Four-point bending experiment

Four-point bending tests were performed by Autograph AG-X Universal Testing Machine which can supply force to an accuracy of 10^{-6} N and displacement of 10^{-6} mm. Laser sensor has to be used for measurement of mid-span deflection because machine stroke may only display displacement of loading position. Laser sensor at hand in lab gives the displacement to an accuracy of 10^{-2} mm, less accurate than stroke to the 4th order. Loads are applied with displacement control at 1mm/min. Photo 2 shows the testing set-up with a specimen during experiment.

Photo 2 Experimental set-up

The corroded side (rust layer) of the specimen is arranged on the upper compressive side as explained in section 2. Bending tests for all corroded specimen, i.e., the composite ones, must be loaded strictly within the elastic range in order to make use of their corresponding un-corroded part for performing the second-time bending tests after cleaning away the rust and meanwhile to satisfy the elastic requirement of physical model given in section 2 as well. For specimen with thickness of 1.0mm, load P (Fig. 3) is controlled below 10N. For specimen with thickness of 1.6mm, load P is controlled below 20N. Loading sensor shows the force of 2P correspondingly. By these force restraint, the estimated stress at the top of the rust layer would be just several MPa, assuring its elastic deformation during loading.

Detail experimental procedures are as follows:

(1) Measurement of h_{com} before loading;
(2) Bending test of corroded specimen composite beam;
(3) Cleaning away the rust according to JCI-SC1;
(4) Measuring the weight of remaining un-corroded steel plate for calculation of the average value of t_s.
(5) Thickness of rust layer t_r is calculated by subtracting t_s from h_{com}.
(6) Bending tests of the un-corroded plate.

Since two loading points directly touch the rust layer (Photo 2), a certain degree initial load was devoted to the deformation of rust layer at that local position. This is the very reason why mid-span deflection is collected for calculating the rigidity instead of loading points, even though laser sensor utilized is not as sensitive as expected.

4. RESULTS AND DISCUSSION

The relationship between load and mid-span deflection obtained from experiments for all the specimens manifest good linearity except for the initial loading stage due to the direct contact between the rust and two loading points. Typically, Fig.6-7 give the load-displacement curves for specimen No. 1.0-1 of the corroded composite beam and its un-corroded one; And Fig.8-9 give for specimen No. 1.6-4. In case of corroded plates, the displacement at the beginning of loading is mostly devoted to the deformation of rust layer under the loading points, illustrated from the displacement by dash-line in Fig.6 and 8. They present an obvious quantity in displacement at loading position as well as an unstable state in mid-span displacement (black solid lines). Displacement in Fig.6 is less than in Fig. 8 because an initial loading has been carried out before launching the formal loading. Consequently, this beginning part should not be taken into account in the consideration of beam's rigidity. Real displacement of the beam occurs thereafter.

The linear tendency function is used for evaluating beam's flexibility, shown by red solid lines in Figs. 6-9, which is the reciprocal of beam's rigidity. For example, from Fig 6-7, we may understand that the rigidity ratio of the corroded 1.0mm-1 beam against its un-corroded one is about:

$$\frac{(EI)_{com}}{E_s I_{s,unc}} = \frac{0.088}{0.059} = 1.4.$$

Substituting into the left of Eq.10, it follows,

$$1.49 = \frac{I_r + nI_s}{nI_{s,unc}}$$

where Young's modulus ratio n is the unique unknown. E_r can be obtained subsequently by E_s/n (Table 2).

Closely looking at the mid-span displacement curve, the linearly proportional increase of mid-span displacement with forces is actually accompanied by some small up and down vibration. This phenomenon is mainly due to the lower accuracy and sensibility of laser sensor compared with high accuracy of load sensor, mentioned in section 3.3. It was not able to

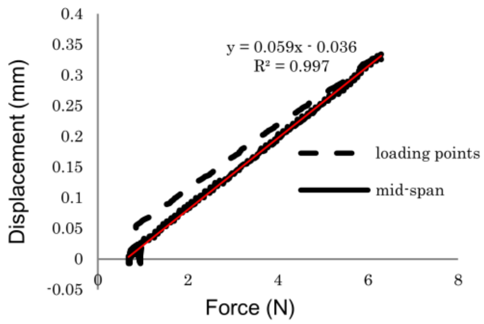


Fig. 6 Displacement-force curve for 1.0-1 corroded beam

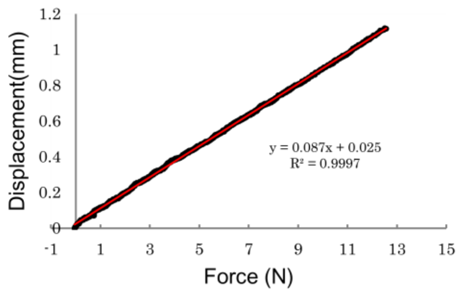


Fig.7 Displacement-force curve for 1.0-1 un-corroded part beam at mid-span

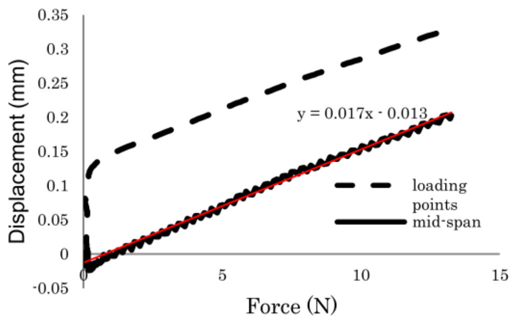


Fig.8 Displacement-force curve for 1.6-4 corroded beam

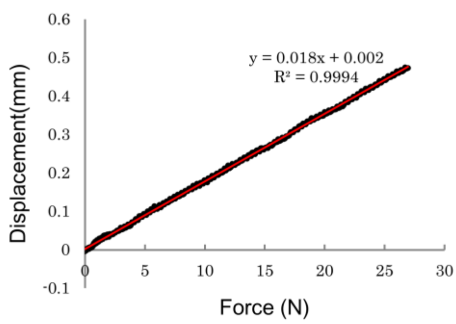


Fig.9 Displacement-force curve for 1.6-4 un-corroded part beam at mid-span

catch necessary smaller displacement change in the process of loading. More delicate measurement in future experiments should be advised.

It may be seen from Table 2 that the rigidity of corroded steel plate $(EI)_{com}$ is on average (of 18 specimens) 1.3 times greater than its un-corroded part $(E_s I_{s,unc})$. Such a change of flexural rigidities result entirely from the existence of rust layer. Ratio of Young's modulus n and corresponding E_r are calculated based on the theory introduced in section 2 and expressed in integral in Table 2. Young's modulus of rust layer obtained is at a range between 1~9GPa, which is in consistent with Ouglova's result [2] of several GPa. Two influential factors may be considered and improved in future study:

(1) Measurement and determination of the thicknesses of rust layer and un-corroded part steel beam.
This may be improved by use of OS or SEM.

(2) More delicate mid-span displacement.
This may be improved by use of a laser-sensor with an accuracy of 10^{-6} mm coincident with that of stroke displacement of loading machine.

5. CONCLUSIONS

A new experimental method for evaluating Young's modulus of rust layer has been proposed by 4-point bending test of simply-supported beam. The basic idea is to look at the corroded steel plate as a composite beam composed of rust layer and un-corroded part steel substrate. Based on classic elastic bending theory, difference of rigidities between composite corroded steel beam and its un-corroded steel beam should lead to present the mechanical properties of rust layer.

Two groups of steel plates with initial thickness of 1mm and 1.6mm respectively are corroded by salt-spraying to construct corroded composite beams. Elastic bending tests are carried out on them and their un-corroded part after removing the rust. Different rigidity ratio is found from load-displacement curve at mid-span. Based on Eq.10, the initial tangent Young's modulus of rust E_r is obtained, which is concluded in a possible range of several GPa.

It is known that rust is not an elastic material. The change of Young's modulus during loading certainly has not been reflected by the bending test in this paper. However, any mechanical properties of rust layer such as stress-strain relationship and Poisson's ratio can be obtained by simply supported bending test if it can be taken as a thin film [7]. The work is on the way by authors now.

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