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MOISTURE ABSORPTION BEHAVIOR OF AEROSPACE CARBON FIBER REINFORCED RESIN MATRIX COMPOSITE STIFFENED PANELS

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Abstract: In order to study the moisture absorption characteristics of carbon fiber reinforced resin matrix composite reinforced wall panels in hot and humid environments, moisture absorption experiments were carried out at 70 ℃ / 85% relative humidity. Combined with the experimental data, a composite reinforced wall panel was proposed. The stage moisture absorption model of this type of structure, and the finite element simulation of the moisture absorption behavior of this type of structure is carried out. The results show that the composite reinforced wall panel complies with Fick's law of moisture absorption in the early stage of moisture absorption, and there is obvious staged moisture absorption phenomenon in the late stage of moisture absorption; the proposed staged moisture absorption model has high analysis accuracy, and the moisture absorption curve of the staged moisture absorption model is consistent with the finite element simulation results Keep consistent, and the calculation error is within 5%. The results of moisture concentration distribution reveal the stage moisture absorption mechanism of composite reinforced wall panels, and the difference in the moisture absorption equilibrium rate of the structure at different thicknesses is the main reason for the stage moisture absorption phenomenon.
Keywords: Composite reinforced siding; Moisture absorption behavior; Moisture absorption model; Moisture concentration distribution

1 HUMID HEAT ENVIRONMENT EXPERIMENT

During actual service, in addition to bearing maneuvering loads, gust loads and other load environments, the composite material reinforced panels widely used in aircraft structures will also be affected by the overall environment and local environment that affect their integrity [1], Such as temperature, humid environment, ultraviolet radiation and chemical corrosion, etc., these environments affect the performance of composite material structures through different mechanisms [2]. In particular, the hygrothermal aging effect of the composite structure will cause changes in the physical/chemical properties of the fibers, matrix and interfaces, reduce the load-bearing performance of the structure, and pose a serious threat to the flight safety of the aircraft. Therefore, it is of great engineering significance to carry out research on the hygrothermal characteristics of composite reinforced panel structures.

At present, domestic and foreign scholars have carried out a lot of research on the hygrothermal properties of carbon fiber reinforced resin matrix composites on the law of moisture absorption and diffusion, the mechanism of hygrothermal aging and the degradation of mechanical properties. In the description of moisture absorption diffusion, the widely used moisture absorption models include Fick diffusion law[3-4], Langmuir two-phase model[5] and vapor boundary condition model[1]; in addition to the above models, Petropoulos[6] considered that moisture Concentration and local stress have an influence on the moisture absorption and diffusion of composite materials, and proposed a one-dimensional and two-dimensional diffusion model including transverse stress and concentration; Grace et al. [7] proposed a three-dimensional Hindered Diffusion Model (HDM); Wong et al. [8] believe that the stage moisture absorption theory can better describe the moisture absorption and diffusion of composite materials. In terms of the mechanism of hygrothermal aging, studies have pointed out that hygrothermal aging is mainly a process of performance degradation of the reinforced fiber, resin matrix, and matrix/fiber interface [9]; carbon fibers basically do not have hygroscopic behavior, but moisture causes chemical reactions of the functional groups on the fiber surface, causing Hydrolysis directly affects the bonding properties of fibers and resins, and then affects the load-carrying properties of composite materials[10]; in high-temperature and high-humidity environments, the hydrophilic groups will undergo chemical reactions, causing polymer breakage and destruction, and the resin-based The chemical structure, mechanical properties and thermal properties of the composite material all affect the interface performance and failure mechanism of the composite material [11]; the interface acts as a "bridge" connecting the fiber and the resin matrix. microcracks, hydrolysis, and debonding. In the research on the degradation of mechanical properties, Zhao Peng et al. [12] pointed out that the irreversible damage of the matrix and interface due to hygrothermal aging is the main reason for the degradation of mechanical properties; The influence of moisture and heat aging on the properties of glass fiber/epoxy resin composites was studied by microscopy and other methods; Zhang Tiejun et al. [14] carried out moisture absorption experiments and shear load-bearing performance experiments of composite material reinforced wall panels in humid and hot environments; Guermazi et al.[14] 15] Carried out experiments on the mechanical properties of carbon fiber epoxy resin-based, glass fiber epoxy resin-based and hybrid fiber composites under 24, 70°C and 90°C water immersion environments.

Existing literature mainly focuses on the hygrothermal performance of laminated panels. There are still few reports on the moisture absorption experiments and moisture absorption behavior of composite reinforced panel structures. Aiming at this problem, this work carried out the wet heat environment experiment of the composite material reinforced wall plate structure. Laws of moisture absorption and diffusion in the environment.

1.1 Experimental Piece

This work is based on the composite material reinforced wall plate structure in literature [16], and its typical section is selected as the moisture absorption test piece. The test piece is made of skin and reinforcement cemented and cured. Its appearance and size are shown in Figure 1 shown.

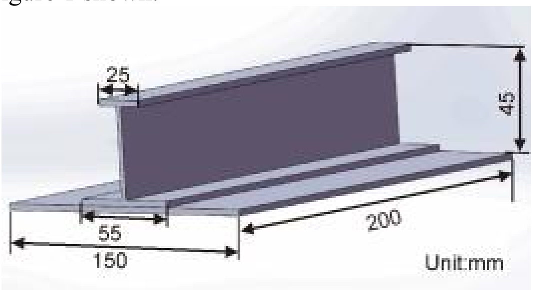

Fig. 1 The shape and structure size of the experimental piece

The material of the experimental piece is composed of high-temperature curing epoxy carbon fiber unidirectional tape BA9916-II/HF10A-3K and carbon fiber twill fabric BA9916-II/H FW220TA. The thickness of a single layer of carbon fiber twill fabric is 0.23mm, and the thickness of the unidirectional tape is 0.125mm, the layering sequence and basic mechanical properties of the materials are shown in Table 1 and Table 2; in Table 1, the superscript "*" indicates fabric, and the rest are unidirectional tape layers. In the hygrothermal experiment of composite reinforced wall panels, there are 3 test pieces, numbered as H-1, H-2 and H-3, and their structural form, material selection, lay-up sequence and preparation process are all consistent.

Table 1 Lamination sequence of stiffened slabs

part	Stack sequence
Skin Stiffener	[-45*/0/-45/0/45/45/0/45/90/-45] s [-45/0/0/45/0/0/-45/0/0/45/90]

Table 2 Material performance parameters of reinforced panels

HF10A-3K	E11/GPa	E22/GPa	G12/GPa	12 v
Materials	103~124	10.492	4.51	0.16
HFW220TA	45~63	52	4.14	0.28

1.2 Experimental Method

The damp heat environment experiment is carried out in the GDJS-1000 high and low temperature alternating damp heat test box, as shown in Figure 2. The temperature/humidity parameter range of the equipment is -20~150℃/30%~98%RH, and the fluctuation range of temperature and humidity is ±0.5℃ and 2%~3%RH. The weighing of the experimental piece is carried out on the JM-B electronic counting balance, the maximum measuring range of this instrument is 300g, and the measurement accuracy is 10-4.

Fig. 2 GDJS-1000 damp heat test chamber

When carrying out the heat and humidity environment experiment, follow the ASTM D 5229/D 5229M-92 (04) experimental standard [4]. First, place the test piece in an environmental chamber at 70°C for drying pretreatment.

When the dehumidification rate of the test piece is stable at a daily mass loss of no more than 0.01%, it can be considered that the test piece is in an engineering dry state, and its mass is recorded. W0; then put it in a 70°C/85%RH environment box to carry out the moisture absorption test, weigh the test piece every 24h and record its mass Wt, when the continuous mass change rate of the test piece is not greater than 0.01 % to end the experiment.

1.3 Experimental Results

After the hot and humid environment experiment is over, the moisture absorption rate of the three test pieces can be obtained from formula (1), and the moisture absorption rate at the same time is averaged.

Mt = $\frac{W_t - W_0}{W_0}$ × 100% (1)

In the formula: Mt is the moisture absorption rate after t hours of moisture absorption; Wt is the mass after t hours of moisture absorption; W0 is the mass of the experimental piece in the engineering dry state. Because the structural form, hygroscopic environment and experimental method of the experimental piece in literature [17] are consistent with this paper, only the material type and layup sequence are different; the structure is composed of medium-temperature cured epoxy carbon fiber unidirectional tape BA9916-II/CCF300, the thickness of a single layer is 0.125mm, and the layering sequence of each part of the structure is [-45/-45/0/-45/0/45/45/0/45/90/-45] s. In order to study the moisture absorption behavior of the reinforced panel structure, the moisture absorption kinetic curve is shown in Figure 3.
Analysis of Figure 3 shows that the moisture absorption curve in literature [17] and the experimental moisture absorption curve show a similar change rule, that is, as the moisture absorption time increases, the square root of the moisture absorption rate with time presents a more obvious hygroscopic phenomenon in stages, and the moisture absorption rate and time The square root of shows an obvious linear relationship within each stage.

2 MOISTURE ABSORPTION MODEL OF COMPOSITE MATERIAL REINFORCED PANEL

2.1 Fick's Law of Diffusion

In the study of moisture absorption behavior of composite materials, the theoretical moisture absorption model can be used to determine the amount of moisture absorbed at a certain moment under certain environmental conditions and the time required to reach a certain level of moisture absorption under specified environmental conditions. The hygroscopic behavior of composite materials, that is, the diffusion behavior of water molecules in composite materials, can usually be described by Fick's law of diffusion, as shown in formula (2).

$\frac{\partial C}{\partial t}$ = Dz × ($\frac{\partial^2 C}{\partial^2 z}$) (2)

In the formula: Dz is the diffusion coefficient (mm2/h); C is the moisture absorption concentration (g/ mm3); t is the moisture absorption time (h); z is the coordinate along the thickness direction of the plate.
The relationship between the moisture absorption rate Mt and the moisture absorption time t can be obtained from formula (2), as shown in formula (3).
Mt = G (t) (M∞ - M0) + M0 (3)
In the formula: M∞ is the equilibrium moisture absorption rate; M0 is the initial moisture absorption rate.
G (t) is a function related to moisture absorption time, which can be approximated by formula (4).
G (t) = 1-exp[-7.3(Dzt/h2) 0.75] (4)
the slope value K of the fitting line in the linear stage of Mt-槡t, the moisture absorption diffusion coefficient can be calculated as shown in formula (5).

Dz = π($\frac{h}{4M_\infty}$)2 (M (槡t $\sqrt{t_2}$ − $\sqrt{t}$ t1))2 (5) [superimposed fragments: 2) M(]

In the formula, M (t1) and M (t2) are the moisture absorption rate at t1 and t2 respectively. From equations (2) ~ (5), the Fick hygroscopic model can be obtained, as shown in equation (6)
Show. The analysis shows that the moisture absorption rate in the Fick moisture absorption model is only related to the slope of the moisture absorption kinetic curve and the moisture absorption time, and has nothing to do with the thickness.
MF (t) = (M∞ - M0) ·
{ 1-exp [-7.3 ($\frac{D_z t}{h^2}$)0.75] }＋M0 (6)
Through linear fitting, the slope of the moisture absorption rate and the square root of time, the moisture absorption diffusion coefficient and the equilibrium moisture absorption rate can be obtained, as shown in Table 3.

Table 3 Parameters of Fick hygroscopic model.

Data	K / (h-1 / 2)	Dz / (mm2 h-1)	M∞/%
Experimental	0.0145	0.0009	0.5813
Reference[17]	0.0241	0.0011	0.902

There is a large error between the Fick moisture absorption curve and the experimental moisture absorption curve in the late stage of moisture absorption. In the early stage of moisture absorption, the experimental moisture absorption curve fits well with the Fick moisture absorption model; when the moisture absorption rate reaches about 60% of the equilibrium moisture absorption rate, there is an obvious staged phenomenon, and the experimental moisture absorption curve is significantly higher than the Fick moisture absorption model analysis results. Literature [18] pointed out that in the early stage of moisture absorption, under the coupling effect of temperature and humidity, water molecules quickly enter the interior of the material through the gaps and cracks; in the late stage of moisture absorption, the moisture absorption mechanism of water molecules is relatively Complex, after the resin absorbs moisture, the polymer in the material will undergo chemical changes, and the material will solidify again to produce a large number of hydrophilic groups, further absorbing moisture, and stage hygroscopic behavior will appear. For the reinforced wall plate structure, in addition to the hygroscopic behavior in the above stage, water molecules do not absorb moisture with equal thickness when they enter the interior of the material along the periphery, and there is a secondary moisture absorption saturation phenomenon in the thickened area of the section (the junction area between the lower edge strip and the skin), that is, the thin plate part reaches the moisture absorption equilibrium first, and the thickened area continues to absorb moisture until the second moisture absorption equilibrium.

2.2 Stage Moisture Absorption Model

In the study of the moisture absorption model of the composite material reinforced wall plate structure, literature [14] aimed at the staged moisture absorption phenomenon of the reinforced wall plate experimental piece, established a staged moisture absorption model, and proposed the moisture absorption balance of the thin plate first, and the moisture absorption balance after the thickened area In addition, the moisture absorption behavior of the two stages is described by Fick's diffusion law, but the fitting effect of the moisture absorption model in the latter stage still has a large error. The analysis shows that in the second stage of the moisture absorption process of the composite material reinforced panel, it is not a simple stepwise segmental function relationship; the structure will be in the moisture absorption process of the coupling of chemical reaction and physical moisture absorption in the late stage of moisture absorption, until the moisture absorption equilibrium;, Fick's diffusion law will no longer be applicable to the description of the late stage of moisture absorption; in order to further analyze the moisture absorption characteristics of the reinforced panel structure, a moisture absorption model of the structure is established.

The moisture absorption process of composite reinforced wallboard is divided into two stages, which are Fick moisture absorption stage and non-Fick moisture absorption stage; in the Fick moisture absorption stage, water molecules diffuse freely and quickly enter the internal defects, cracks and resin interior of composite materials At the same time, the thin plate area reaches the moisture absorption stage of the composite material chemical reaction in advance, and the diffusion of water molecules in this stage conforms to Fick's diffusion law; in the non-Fick moisture absorption stage, some composite materials enter the chemical reaction stage, the resin properties change, and a large number of hydrophilic groups are generated. The chain movement of the resin and the transition ability of water molecules in the matrix decrease, resulting in a slowing of the moisture absorption rate[19]. until the structure reaches moisture absorption equilibrium.

Stage hygroscopic behavior for composite reinforced wall panel structures. Before establishing the stage hygroscopic model, the following assumptions are made according to the cross-sectional characteristics of the structure and the hygroscopic environment:

(1) Fick's law of diffusion has good applicability in describing the initial moisture absorption of composite reinforced panels;

(2) The thickness of the section of the reinforced wall plate is very small compared to its width (the thickness/width of the web plate is 0.06, and the thickness/width of the wall plate is 0.02), so the influence of the side and boundary conditions on the moisture absorption rate can be ignored Impact;

(3) The hygroscopic environment of the reinforced panel remains constant, and the initial moisture absorption rate is small and negligible.

According to the above assumptions, the stage moisture absorption model of composite material reinforced panel structure is established as shown in formula (7).

$M(t) = MF(t) + MNF(t) =$

$M\infty G(t) + (1-\varphi) M\infty H(t)$ (7)

In the formula, φ is the ratio of the maximum moisture absorption rate in the Fick moisture absorption section and non-Fick moisture absorption section, that is, φ = MF, max/MNF, max; H (t) is the moisture absorption function in the non-Fick stage, and the expression is as follows: 8) as shown.

$H(t) = 1-\exp[-(\alpha \langle t-t0 \rangle)\beta]$ (8)

Simultaneous formulas (6) ~ (8), the stage moisture absorption model of composite material reinforced panel structure can be obtained, as shown in formula (9).

$M(t) = M\infty \{1-\exp[-7.3(Dzt/h2)\,3/4]\} +$

$(1-\varphi)M\infty \{1-\exp[-(\alpha \langle t-t0 \rangle)\beta]\}$ (9)

In the formula, t0 is the initial moisture absorption time into the non-Fick segment; α, β are the moisture absorption coefficients of the non-Fick segment; <t-t0> is defined as the non-Fick segment moisture absorption time, when the

moisture absorption time t ≤ t0, When Fick moisture absorption occurs, MNF (t) = 0; when the moisture absorption time tVt0, the stiffened panel structure enters the non-Fick moisture absorption stage.
Combined with the analysis of the specific form-stage moisture absorption process of the stiffened panel section, it is assumed that the Fick moisture absorption stage of the reinforced panel is mainly reflected in the thin plate area of the structure, so the maximum moisture absorption ratio of the two stages φ can be approximated as the thin plate area accounted for by the stiffened panel section ratio. Reinforced panels with different cross-sectional shapes have different maximum moisture absorption ratios φ. For the "I"-shaped test piece used in this work, the ratio φ is shown in formula (10).
φ = LU + LW + LS (10)
When solving the moisture absorption coefficient α in the non-Fick stage, the experimental data Hexp (t) of this stage is shown in formula (11). In the formula, Mexp (t) is the actual moisture absorption rate of the experimental piece; MF (t) is the theoretical moisture absorption rate in the Fick moisture absorption stage. Define the stage coefficient k, that is, when the moisture absorption MF (t) = kφM∞, the material enters the non-Fick moisture absorption stage, and the corresponding moisture absorption time is t0. Usually, when the moisture absorption rate of carbon fiber resin-based composite materials reaches 0.7~0.8 times the Fick moisture absorption saturation rate, moisture absorption enters the chemical reaction.
stage.

Hexp (t) = $\frac{M_{\exp}(t) - M_F(t)}{(1-\varphi)M_\infty}$ t V t0 (11)

From the above formula, the expression of non-Fick moisture absorption coefficient α can be analyzed as
ln{-ln[1-Hexp (t)] }= β×lnα+β×ln[t-t0] (12)
Combined with the experimental data, formula (12) can be regarded as a linear function, and the values of α and β can be solved respectively according to the slope of the linear fitting and the intersection point with the y-axis, and then the moisture absorption coefficients α and β are brought into formula (9), Then the stage moisture absorption model of the composite material reinforced panel can be obtained.
According to the moisture absorption data and structural size of the composite reinforced wall panel experimental piece, the moisture absorption experimental data of the same structural size experimental piece in the literature [17] is used as the verification data, and the stage moisture absorption model is used for analysis. The relevant model parameters are shown in Table 4 shown.

Table 4 Parameters of moisture absorption model for composite reinforced panels

Parameter	Experiment	Reference[17]
k	0.806	0.760
φ	0.796	0.796
alpha	5.16×10-5	5.61×10-4
beta	0.233	0.879
Dz / (mm2 h-1)	0.0009	0.0011
M∞/%	0.5813	0.902
t0/h	480	408

Putting the solved parameters of the staged moisture absorption model into formula (9), combined with the analysis of experimental data and literature data, it can be seen that the staged moisture absorption model of the composite material reinforced panel structure can describe the law of moisture absorption and diffusion of this type of structure well, indicating that Stage hygroscopic behavior exists objectively in the hygroscopic phenomenon of composite material reinforced panel structure. The error of the Fick moisture absorption model is about 10% when describing the moisture absorption characteristics of the reinforced wall panel structure; the error of the stage moisture absorption model is controlled within 5% (the error is relatively large at the initial moisture absorption); The analysis accuracy is high when considering the moisture absorption characteristics of the board; the literature data verifies the applicability of the stage moisture absorption model.

3 FINITE ELEMENT SIMULATION OF MOISTURE ABSORPTION BEHAVIOR OF COMPOSITE MATERIAL REINFORCED PANEL

3.1 Fick Hygroscopic Model

In order to simulate the moisture absorption behavior of the composite material reinforced panel structure, a finite element model with the same size as the experimental piece was established in Abaqus software, as shown in Figure 3.

Fig. 3 Finite Element Model

The unit type of the model is DC3D20, and the total number of units is 507200; according to the material parameters of the experimental piece and the data of the moisture absorption experiment, the corresponding material properties are defined in the mass diffusion module. According to the moisture absorption state of the experimental piece in the environmental chamber, the boundary condition is defined as the equilibrium moisture absorption rate, and the moisture absorption and diffusion from the four sides of the model (except the contact surface between the reinforcement and the skin) are set, and the ambient temperature is 70°C; in order to be consistent with the moisture absorption experiment The data acquisition time is consistent, and the calculation is performed with 24h as an incremental step. The total analysis time is 1728h, which is consistent with the experimental equilibrium time.

3.2 Simulation Result Analysis

Through the finite element analysis of the moisture absorption behavior of the composite material reinforced wall plate structure, the comparison and error analysis of the moisture absorption kinetic curve of the reinforced wall plate structure and the experimental results are obtained. The finite element moisture absorption results are in good agreement with the experimental results, almost consistent with the experimental moisture absorption kinetic curve; in the early stage of the moisture absorption experiment, the error of the finite element analysis is relatively large, and some errors exceed 10%; in the late stage of moisture absorption, the error is within 5%. Compared with the stage moisture absorption model, the errors of the two are almost the same, but in the early stage of moisture absorption, the error of the stage moisture absorption model is relatively small. Although there are essential differences between the finite element analysis and the staged moisture absorption model, both can describe the moisture absorption and diffusion characteristics of this type of structure well, which verifies the accuracy of the staged moisture absorption model.

Through the finite element simulation, the diffusion law of the moisture concentration in the structure of the reinforced panel structure in the initial stage of the hot and humid environment can be obtained. In the early stage of moisture absorption and diffusion, moisture enters the interior of the material along the surface of the material, and the surface of the material first reaches the moisture absorption equilibrium. As the moisture absorption time increases, the moisture gradually diffuses into the interior of the material, and the moisture absorption equilibrium time along the material thickness direction has obvious difference. In the later stage of moisture absorption, the thin plate area has gradually tended to the moisture absorption equilibrium, and the increased area is still in the rapid moisture absorption stage, but the hygroscopic water in the thickened area mainly comes from the diffusion of surface water molecules, and there is a big difference between the hygroscopic boundary conditions and the surface moisture absorption; therefore, the moisture absorption rate is relatively slow at this time, but the overall moisture absorption rate of the structure is still increasing slowly until the structure completely reaches the moisture absorption equilibrium. When the reinforced wall panel structure absorbs moisture for 1728 hours, and the moisture absorption change rate is less than 0.01%, it can be considered that the composite material reinforced wall panel structure has approximately reached the moisture absorption balance.

When the moisture absorption time reaches 480h, that is, after 20 days of moisture absorption, there is an obvious stage phenomenon. It is considered that the structure enters the non-Fick moisture absorption stage at this time, which is almost the same as the moisture absorption days corresponding to the stage moisture absorption coefficient k=0.806 in the stage moisture absorption model. be consistent. It shows that the stage moisture absorption model and the finite element analysis method can describe the moisture absorption and diffusion law of the stiffened panel structure well, and have high analysis precision.

In order to further explore the diffusion characteristics of moisture concentration into the interior along the surface of the material, the reinforced panel structure is divided into two parts according to the thickness, namely the thin plate area and the thickened area. Along the material thickness direction, the moisture absorption rate corresponding to each node at different times is selected.

In the whole process of moisture absorption, the closer to the moisture absorption surface, the earlier the moisture absorption equilibrium is reached, and the moisture absorption concentration is unevenly distributed along the thickness before the structure moisture absorption equilibrium. Before the moisture absorption time reaches 1728h, although there are differences in the moisture absorption equilibrium time in different regions, there is no absolute moisture absorption equilibrium, that is, the thin plate area is still in the slow moisture absorption process in the late stage of moisture absorption, which is consistent with the previously proposed stage moisture absorption model.

4 CONCLUSION

(1) The initial hygroscopicity of the composite reinforced wallboard conforms to Fick's diffusion law; in the late stage of moisture absorption, there is an obvious hygroscopic behavior in stages, and Fick's diffusion law is not suitable for the description of the hygroscopic behavior of this type of structure in the later stage.
(2) The staged moisture absorption model of the composite material reinforced wall plate proposed has high analysis accuracy, the calculation error is about 5% in the early stage of moisture absorption, and the error in the late stage of moisture absorption is within 2.5%, that is, the staged moisture absorption model has better performance. Describe the moisture absorption and diffusion behavior of moisture inside the composite reinforced panel structure.
(3) The finite element analysis results are almost consistent with the calculation results of the stage moisture absorption model, and the analysis error is about 5%, which has a high analysis accuracy.
(4) The moisture concentration distribution characteristics of the stiffened panel section are consistent with the proposed stage moisture absorption behavior, and the difference in moisture absorption equilibrium rate of different structural thicknesses is the main reason for the stage moisture absorption phenomenon.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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