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***ORIGINAL ARTICLE***

# Experimental research on formaldehyde emission characteristics from glubam by climate chamber test

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**Abstract:** Glued laminated bamboo (glubam) is a type of bamboo-based lamina, and manufactured by pressure lamination of phenol-formaldehyde saturated bamboo strips under elevated temperature. Estimating, controlling, and limiting the formaldehyde release from glubam are important issues in indoor air quality of building with glubam. This study investigates formaldehyde emission characteristics from two types of glubam under different conditions including temperature, relative humidity, edge treatment, and surface covering material. A series of formaldehyde concentration tests were performed using 1 m$^3$ climate chamber. The results indicate that the peak values of the formaldehyde concentration of glubam specimens under all testing conditions are lower than 0.124 mg/m$^3$, and thus can be classified as Class $E_1$ according to EN 13986. An analysis model was provided to estimate formaldehyde release based on the test data and a first-order decay model. Initial formaldehyde emission rate $E_0$ and decay rate constant $k$ in the proposed model was utilized for comparison and analysis of the experimental parameters. This investigation reveals that the temperature and relative humidity have significant influence on the formaldehyde emission characteristics of glubam boards. Sealing cutting edges and covering surface layer of the samples can significantly reduce the releasing rate and amount of formaldehyde from glubam.

**Keywords:** Bamboo; glubam; formaldehyde emission; climate chamber

## 1 Introduction

The building industry plays a very important role in natural resource and energy consumption as well as the emission of greenhouse gases caused by the conventional structural materials, such as steel and cement. Accordingly, using biomass building materials to replace steel and cement to some degree is a need for minimizing the impact environment and achieving sustainable development and possible carbon neutrality. As a type of environmental-friendly building material, bamboo has gradually attracted attention in the civil engineering community, and it is considered a competitive material for wood and wood-based composites due to its excellent comprehensive characteristics, including a high strength-to-weight ratio, low carbon emission, fast-growing and inexpensive [1-2]. Therefore,

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developing bamboo structures gain popularity in those countries and regions with rich bamboo resources, such as China, Southeast Asia, and Africa [3-4]. However, round bamboo culms are not suitable as the structural components for modern structures considering the irregular shape and greater variability of mechanical performance [5-6]. Therefore, engineered bamboo, an innovative bamboo-based composite material, has been developed rapidly in the past decade, mainly including glued laminated bamboo (glubam) and bamboo scrimber [7-11]. Engineered bamboo products are manufactured with standard dimensions and stable mechanical properties through basic processing, corresponding that the bamboo culms are split into bamboo strip and then laminated together by adhesive [4, 12, 13].

As a new type of biomass building engineered material, glubam exhibits relatively higher mechanical properties compared with the common engineered wood products–glulam [2, 12, 14, 15]. Compared with other engineered bamboo products, such as bamboo scrimber, glubam possesses the relatively simple demands of manufacturing technique and higher bamboo utilization efficiency, which means the cost price of glubam is lower [4, 7,10]. Through systematic research, some demonstration buildings have been designed and constructed with glubam [4, 16, 17, 18], including the lightweight glubam frame houses and the mass glubam structure (or glubam beam-column structure), corresponding to **Fig. 1** and **Fig. 2**, respectively.


(a) Under construction (b) Completion

**Fig. 1.** Light glubam frame structure house (Zizhuyuan Park, Beijing).


(a) Under construction (b) Completion

**Fig. 2.** Glubam beam-column structure building (Meixihu, Changsha).

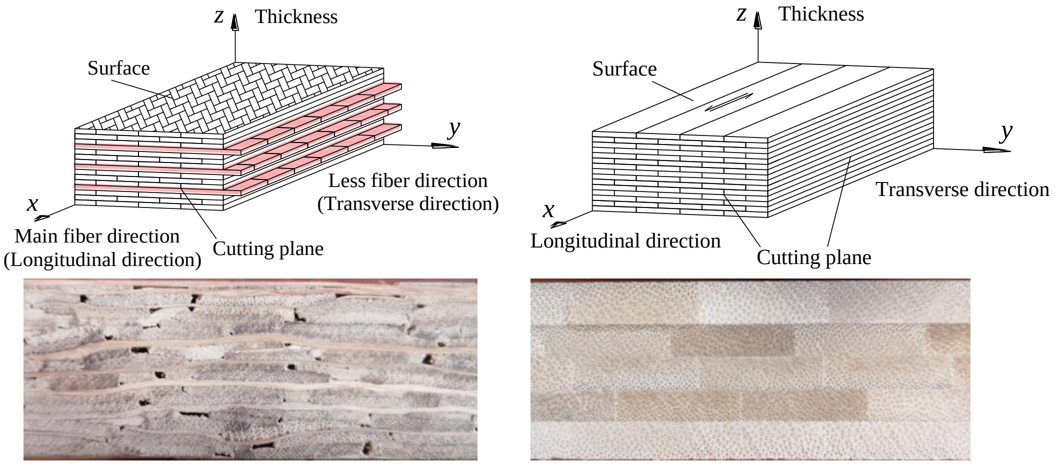
As a typical structural material used in outdoor conditions, the phenol-formaldehyde resin is indispensable in the hot-press lamination process of glubam boards. Now, a type of glubam board covered by bamboo-based decorative layer has been used in some mass glubam structure buildings to meet the requirement of the surface of glubam elements directly acting as the decorative surface. Thus, the adhesives that involve formaldehyde can be possibly released during usage and may cause problems such as indoor air quality [19-20]. Formaldehyde is a type of colorless gas with strongly pungent odor at normal atmospheric temperature [21], and it can cause protein denaturation and induce cancer [22]. The formaldehyde coming from manmade plates and furniture in the indoor built environment mainly originates from three aspects. Firstly, raw material itself of wood or bamboo is decomposed and releases formaldehyde. Secondly, adhesive contains free formaldehyde which could not react completely in the hot-pressing process. Free formaldehyde in manmade board will release and pollute indoor air, which is the main resource of formaldehyde in indoor. Thirdly, the resin in manmade board will be decomposed and lead to formaldehyde emission during usage [23]. As the basic structural material for modern bamboo buildings, it is very important to study the air volatilization characteristics of glubam.

At present, the peak value of the formaldehyde concentration is used only as a performance indicator of engineered bamboo. The systematic research article about formaldehyde emission from engineered bamboo has not been published yet. To expand the application range of glubam boards from outdoor to indoor, the study attempts to evaluate the formaldehyde emission characteristics of glubam boards under different conditions. A series of tests were conducted on glubam by using 1 m$^3$ climate chamber. The program involves the two types of glubam, temperature, relative humidity, edge treatment, and surface covering material, which are selected as experimental parameters. In addition, an analysis model was provided to estimate formaldehyde release from glubam board based on the test data and a common first-order decay model.

## 2 Experimental program

### 2.1 Glubam board

The glubam can be divided into thick-strip and thin-strip glubams, as illustrated in **Figs. 3**a~b [2, 3, 11, 24, 25], where planes perpendicular and parallel to the z-axis are surfaces and cutting planes, respectively. Thin-strip glubam (TN glubam) is produced by laminating the longitudinal direction/main fiber direction (the *x*-axis) and transverse direction/less fiber direction (the *y*-axis) bamboo sliver curtains, corresponding the size of bamboo sliver is irregular and approximately 2 mm thick and 20mm wide, while the thick-strip glubam (TK glubam) is made by pressure gluing a few layers of unidirectional fine planed bamboo strips with about 5 mm thick and 20 mm wide, as shown in **Fig. 3**a and **Fig. 3**b, respectively. In the current study, the size of the TN glubam board is 28 mm thick, 2400 mm long, and 1200 mm wide with a longitudinal-transverse bamboo fiber ratio of 4:1, and the size of the TK glubam board is 20 mm thick, 2,000 mm long, and 300 mm wide, respectively.



(a) TN glubam (*x*-*z* section) (b) TK glubam (*x*-*z* section)

**Fig. 3.** Glubam board.

Till now, three types of TN glubam boards are used in the actual projects, which have similar lamination configurations but with different surface covering materials according to different needs. Generally, the conventional TN glubam board is covered by a layer of waterproof material on two surfaces for using in outdoor conditions, as shown in **Fig. 4**a. For reducing costs, the plain TN glubam board is usually utilized in the condition without contact with water, especially for using in the indoor environment, corresponding that its surface is only covered by a layer of bidirectional bamboo mat, as shown in **Fig. 4**b. Besides, a type of TN glubam board has been presented for meeting the requirement that glubam is directly exposed as the decorative surface. In this situation, a layer of bamboo-based decorative material is selected as the covering layer, as shown in **Fig. 4**c.

(a) Waterproof layer surface (TNG-S1) (b) Bamboo mat surface (TNG-C2)

(c) Bamboo-based decorative surface (TNG-C1)　(d) Unsealed edges (TNG-E1)

(e) TK glubam (TKG-S1)　(f) Samples in climate chamber

**Fig. 4.** Glubam samples.

In this study, TK glubam provided by a local manufacturer (Hunan province, China) was tested as a contrast, which was glued with urea-formaldehyde resin in the hot-press lamination process. The TK glubam specimen has the same size as the TN glubam specimen, as shown in **Fig. 4**e. The mechanical properties of glubam were obtained according to ISO 23478:2022 [26], as presented in **Tab. 1**. The moisture content of the TN and TK glubam specimens ranged from 11% to 13% and from 12% to 14%, respectively, also measured in accordance with ISO 23478:2022 [26].

**Table 1.** Basic properties of glubam.

| Index | TN glubam[a] | TK glubam[b] |
|---|---|---|
| Compressive strength parallel to the grain (MPa) | 51.6 | 57.7 |
| Tensile strength parallel to the grain (MPa) | 82.5 | 119.3 |
| Bending strength parallel to the grain (MPa) | 91.3 | 104.6 |
| Elastic modulus (MPa) | 9460 | 9052 |
| Density (kg/m$^3$) | 851 | 631 |

[a]TN glubam: thin-strip glubam, [b]TK glubam: thick-strip glubam

## 2.2 Test procedures and equipment

The basic principle of the climate chamber test is that specimens with a total surface area of 1 m$^2$ are placed in the 1 m$^3$ chamber, in which the test parameters of temperature, relative humidity and air ventilation rate are kept constant. Formaldehyde released from specimens is mixed with the air in the climate chamber. Through drawing out a certain amount of air $V_{\mathrm{air}}$ from the chamber, the formaldehyde mixed in the air is dissolved in water. Then, the formaldehyde emission can be determined by measuring the formaldehyde concentration $\rho(t)$ in the liquid, defined as follows,

$$\rho(t) = G / V_{air} \tag{1}$$

where $t$ and $G$ are the duration of the experiment from the beginning and the amount of formaldehyde dissolved in water, respectively.

A climate chamber with volume of 1 m$^3$, QWH-1000A type produced by Jinan Instruments, China, was selected in this investigation, in which the parameters of temperature, relative humidity, and ventilation rate can be set and accurately controlled. For this equipment, the adjustment range of temperature and relative humidity (RH) is (10~30) ℃ ± 0.5 ℃ and (20~80) % ± 2% respectively. The inner wall of the chamber is made of stainless steel plates and the sealing material of chamber is a type of non-absorption inert material.

The investigation in current study was performed according to EN 717-1 [27]. Conditions of the standard test in the climate chamber correspond to the panel samples with the total surface area of 1 $m^2$, the test temperature, and relative humidity (RH) in the range of (23 ± 0.5) ℃ and (45 ± 3) %, respectively. Quantitative analysis of formaldehyde is conducted by the acetyl-acetone spectrophotometric method.

It should be mentioned that glubam is used as structural material with typically larger volume and relatively fewer surface areas and edge exposure, compared with the current study based on the existing specifications for decoration boards. Thus, the study may be considered as the worst-case study.

### 2.3 Test design and procedure

Glubam boards were randomly selected from a batch of products and then were cut into square specimens with the size of 500 mm. In order to obtain the same ratio of the length of open edges $U$ to the surface area $A$ ( i.e., $U/A$ = 1.5 m/$m^2$ ) for test pieces in the climate chamber, four cutting planes/edges of each square glubam sample were partially sealed with Aluminum foil tapes in accordance with EN 717-1 [27], as shown in Fig. 4a. Only one group, the TNG-E1 in **Tab. 2**, was tested without sealed edges in order to evaluate the influence of edge-sealing, as shown in **Fig. 4**d. It should be noted that each group composed of two identical specimens in this test for meeting the requirement of total surfaces area of 1 $m^2$ in the climate chamber, as shown in **Fig. 4**f.

**Table 2.** Details of specimens.

| Test group | Glubam type | Temperature | Relative humidity | Edge treatment | Covering material | Experiment parameter |
|---|---|---|---|---|---|---|
| B-S1 | TN | 23℃ | 45% | - | - | Background concentration |
| B-S2 | TN | 23℃ | 45% | - | - | Background concentration |
| TNG-S1 | TN | 23℃ | 45% | Sealed | Waterproof | Standard test |
| TNG-S2 | TN | 23℃ | 45% | Sealed | Waterproof | Standard test |
| TNG-T1 | TN | 16℃ | 45% | Sealed | Waterproof | Temperature |
| TNG-T2 | TN | 30℃ | 45% | Sealed | Waterproof | Temperature |
| TNG-R1 | TN | 23℃ | 25% | Sealed | Waterproof | Relative humidity |
| TNG-R2 | TN | 23℃ | 65% | Sealed | Waterproof | Relative humidity |
| TNG-E1 | TN | 23℃ | 45% | Unsealed | Waterproof | Edge treatment |
| TNG-C1 | TN | 23℃ | 45% | Sealed | Decorative layer | Covering material |
| TNG-C2 | TN | 23℃ | 45% | Sealed | Bamboo mat | Covering material |
| TKG-S1 | TK | 23℃ | 45% | Sealed | - | Material type (Standard test) |

Twelve groups of specimens were tested in this investigation, and they can be classified into three types: background concentration test (B), TN glubam test (TNG) and TK glubam test (TKG). It should be noted that the climate chamber was empty (without glubam sample) for background concentration test, and the main purpose was to verify the working stability of the equipment. The standard test is used to assess the grade of glubam in accordance with formaldehyde emission, and the testing results from non-standard tests are used to analyze the formaldehyde emission characteristics from glubam boards under different conditions.

In **Tab. 2**, each group is named as test type (B, TNG and TKG) followed by test parameter (S, T, R, E and C) and the parameter level (1 and 2), in which the test parameter of S, T, R, E and C denotes the standard test and different test parameters of temperature, relative humidity, edge treatment (unsealed) and covering material, respectively. For instance, TNG-T1 designates the TN glubam group was tested under the low temperature condition. In this investigation, a repeated standard test (TNG-S2) was used to verify the reproducibility of the formaldehyde release law of the TN glubam board. Five series of test groups can be drawn from **Tab. 2** according to different experimental parameters, such as the TNG-S1 and TKG-S1 for the type of engineered bamboo, the TNG-S1, TNG-T1 and TNG-T2 for the temperature, the TNG-S1, TNG-R1 and TNG-R2 for the relative humidity, the TNG-S1 and TNS-E1 for the edge treatment, and the TNG-S1, TNG-C1 and TNG-C2 for covering material. It should be stressed here that the range of temperature and relative humidity are selected respectively from

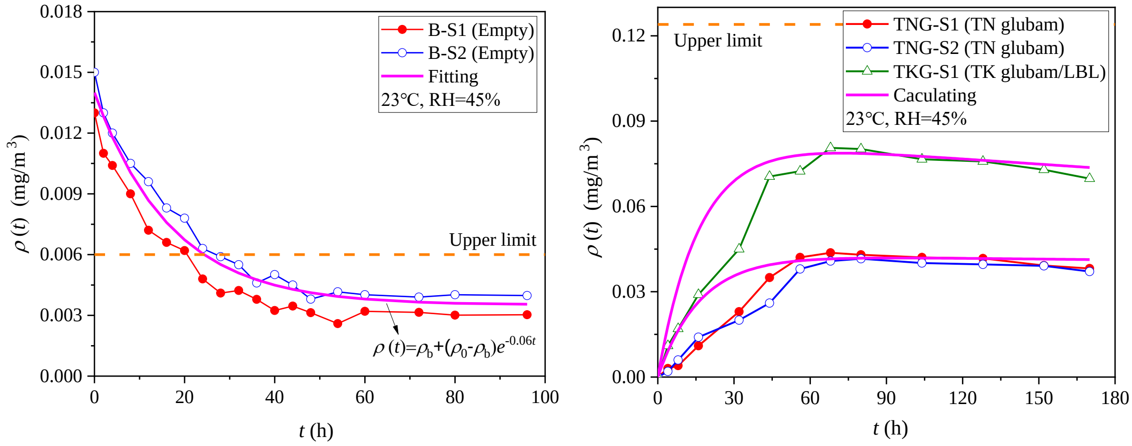
16 °C~30 °C and 25%~65% in this study considering the limited adjustment range of climate chamber.

In this investigation, the air needs to be purified with two processes before entering the climate chamber: the first is particulate filter and the second is distilled water purification. During testing, the formaldehyde concentration is sampled on specific time points, corresponding to 0 h, 2 h, 4 h, 8 h, 16 h, 32 h, 44 h, 56 h, 68 h, 80 h, 104 h, 128 h, 152 h, and 170 h. The test cycle is seven days for each group except for background concentration tests, and the relationships between formaldehyde concentration and time can be obtained. After testing, all specimens had been checked carefully. No obvious damage could be observed on the surfaces and sealed edges for all glubam samples.

## 3 Experimental results

### 3.1 Background concentration tests

Main test results are listed in **Tab. 3**, and relationships between the formaldehyde concentration in the chamber $\rho(t)$ and the test time t for the standard and non-standard conditions are also presented in **Fig. 5** and **Fig. 6,** respectively. Two repeat tests of B-S1 and B-S2 were performed under standard conditions without setting glubam sample in the chamber for evaluating the fluctuation of the background concentration of formaldehyde $\rho_b$.It can be observed in **Fig. 5**a that the background concentration of formaldehyde in the climate chamber nearly stabilized after about 48h from beginning of the test. Therefore, the equipment was kept empty for over 48 hours before each actual test. Then, the $\rho_b$ was sampled three times continuously. If the background concentration stabilized, this value of $\rho_b$ would be recorded for correcting test results. The background concentration in the chamber fluctuated from 0.002 mg/m$^3$ to 0.004 mg/m$^3$ in this investigation, and the value was smaller than the upper limit requirement of 0.006 mg/m$^3$ in accordance with EN 717-1 [27].



(a) Background concentration tests (b) Standard tests

**Fig. 5.** Formaldehyde concentration curves under standard conditions.

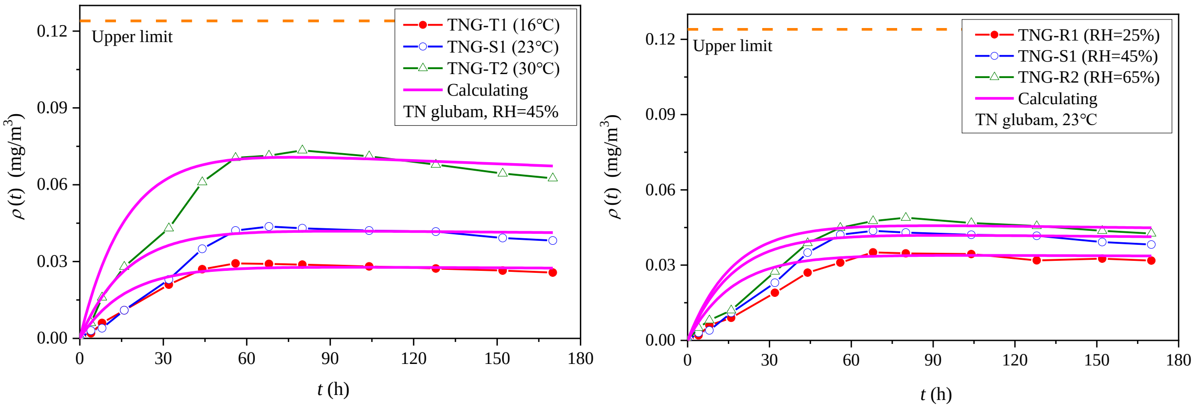
### 3.2 Standard tests

TN glubam standard tests were conducted twice on the different samples. Two correlation curves of $\rho(t)$ and $t$ are presented in **Fig. 5**b. It can be seen that the two curves are close to each other and the difference in the peak value, $\rho_p$, between the tests is less than 5%, showing acceptable repeatability. Besides, it can be seen in **Fig. 6**b that the developing trend of the $\rho(t)$ can be divided into three stages, as follows: firstly, the formaldehyde concentration increases rapidly in the initial 10 hours. Then, the concentration rises slowly until its peak value followed by a long stable stage. Finally, the formaldehyde concentration shows a slightly downward trend at the end of the test.

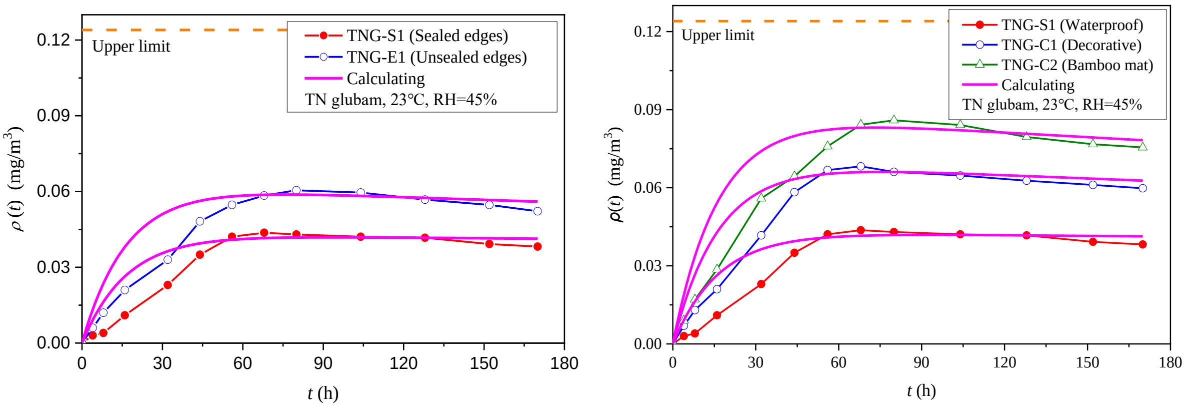
The formaldehyde concentration curve of TK glubam standard test is similar to that of the standard test result from TN glubam, which also includes three stages, as shown in **Fig. 5**b. However, the formaldehyde release rate of TK glubam in the initial stage is significantly faster than that of TN glubam. Under standard test conditions, the peak formaldehyde concentration $\rho_p$ of TK glubam is nearly as much as 1.8 times than that of TN glubam.

### 3.3 Non-standard tests

Correlation curves of $\rho(t)$ and time duration t of non-standard TN glubam tests are presented in **Figs. 6**a~d in accordance with experimental parameters of the temperature, relative humidity, edge treatment, and covering material, respectively. It is found that the curves exhibit a similar developing trend as that of the standard test. However, the peak value of the formaldehyde concentration $\rho_\mathrm{p}$ of each group is related to the testing conditions.



(a) Temperature series (b) Relative humidity series



(c) Edge treatment series (d) Covering material series

**Fig. 6.** Formaldehyde concentration curves under different conditions.

**Figure 6**a shows the curves of $\rho(t)$ under different temperatures, which is an important effect on formaldehyde emission. Generally, the peak value of formaldehyde concentration exhibits an accelerating upward trend according to the temperature increases. The value of $\rho_\mathrm{p}$ under standard temperature (23 ℃) and high temperature (30 ℃) increase about 50% and 150% compared with low temperature conditions (16 ℃), respectively.

The relative humidity also shows a certain degree influence on formaldehyde emission, as shown in **Fig. 6**b. The $\rho_\mathrm{p}$ increases as the relative humidity increases, and the increasing rate is related to the relative humidity. For example, the value of $\rho_\mathrm{p}$ increases about 25% as relative humidity varied from 25% to 45%, while the $\rho_\mathrm{p}$ only increases about 12% as relative humidity varied from 45% to 65%. On the other hand, the influence of the relative humidity on the formaldehyde concentration is smaller than that of the temperature by comparing the test data in **Tab. 3**.

Sealing edges can also affect formaldehyde emission by decreasing the surface area of glubam specimen. **Figure 6**c provides the formaldehyde concentration curves of TNG-E1 and TNG-S1, with sealed and unsealed edges, respectively. In the early 10 hours of the beginning of the test, the formaldehyde concentration of unsealed samples is much higher than that of sealed samples, and the $\rho_\mathrm{p}$ of the former exceeds nearly 40% compared with the latter. Therefore, sealing edges is an important measure to reduce formaldehyde release from glubam board. On the other hand, the formaldehyde concentration of unsealed group shows relatively obvious decay in the end stage of the test, as shown in **Fig. 6**c.

Glubam samples with different covering material exhibit obviously different characteristics with formaldehyde emission. It is observed in **Fig. 6**d that the formaldehyde release rate of the TNG-C1 and TNG-C2 covered by the bamboo-based decorative layer and bamboo mat, respectively, are significantly higher than that of the TNG-S1 covered by the waterproof material, and the $\rho_p$ of TNG-C2 is almost the highest in all test groups. Compared with the TNG-S1, the $\rho_p$ of the TNG-C1 and TNG-C2 increase 56% and 97%, respectively, indicating that using waterproof material covering surface is an effective measure for preventing formaldehyde release from glubam board.

According to EN 13986+A1-2015 [28], the formaldehyde concentration upper limit is 0.124 mg/m$^3$ for the wood-based panel which is directly used as the indoor decoration tested by 1 m$^3$ climate chamber under the standard test conditions. The maximum formaldehyde concentration of TNG-S1 and TNG-S2 are significantly smaller than the upper limit. Therefore, the TN glubam is classified as Class $E_1$ according to the requirements of EN 13986+A1-2015 [28]. Recently, a new Chinese standard, GB/T 39600-2021 [29], on formaldehyde emission grading for wood-based panels and finishing products has been issued, in which the upper limit of Class $E_0$ is 0.05 mg/m$^3$. The testing results show that the conventional TN glubam board, covered by waterproof material, can also be classified as Class $E_0$ in accordance with GB/T 39600-2021 [29]. The maximum formaldehyde concentration of the TK glubam provided by a local manufacturer is also less than 0.124 mg/m$^3$, while its peak value is larger than that of the typical TN glubam group, TNG-S1. It can also be found in **Tab. 3** and **Fig. 5** that all test results of TN glubam groups are less than 0.124 mg/m$^3$ even under non-standard conditions.

### 3.4 Formaldehyde emission model

To simplify analysis, this process of formaldehyde emission can be considered by dividing it into four stages based on studies on total volatile organic compounds from pressed wood products conducted by Guo et al. [30]. Firstly, the free formaldehyde diffuses from the inside to the surface of glubam board. Secondly, the free formaldehyde volatilizes to the air interface layer in the chamber. Then, the formaldehyde transmits in the airflow boundary layer. Lastly, the formaldehyde mixes and diffuses with the mainstream airflow in the chamber. Therefore, the tested formaldehyde concentration is not only related to the content of the free formaldehyde and the performance of glubam board but also is affected by the environment and flow characteristics in the climate chamber [31].

In this study, a first-order decay model is selected as a reference which is a commonly used and simple model in analyzing volatile organic compounds (VOC) [32-33], and the general formula is expressed as follows,

$$E(t) = E_0 e^{-kt} \tag{2}$$

where $E(t)$ is formaldehyde emission from the unit area of glubam board in unit time, with the unit of mg/(h m$^2$); $t$ is the test time, with the unit of h (hour); $E_0$ is the initial formaldehyde emission rate at the beginning, with the unit of mg/(h m$^2$); $k$ is the decay rate constant, with the unit of h$^{-1}$.

**Equation 2** can characterize formaldehyde emission of glubam board. However, it should be noted that the test data are only the formaldehyde concentration $\rho(t)$ in airflow of the climate chamber instead of actual formaldehyde emission $E(t)$ from glubam board. So the relationship between $E(t)$ and $\rho(t)$ needs to be created [34]. For simplifying analysis, two hypotheses are presented, as follows,

(1) The volume of climate chamber $V$ is constant with ignoring the influence of samples.

(2) The air input $u$ in unit time is equal to the air output $p$ in unit time, and the total air volume in the chamber is constant at any time during the test.

Then, the change of formaldehyde concentration $\rho(t)$ from any time $t$ to $t+\Delta t$ in the chamber can be described as follows,

$$\rho(t+\Delta t) - \rho(t) = \left[ E(t) \cdot A \cdot \Delta t - \alpha \cdot \rho(t) \cdot p \cdot \Delta t \right] / V \tag{3}$$

in which, $A$ is the total surface area of samples in the climate chamber; $\alpha$ is the correction factor for considering the influence from the test environment and test equipment, which cannot be ignored according to the result of the background concentration tests, as shown in **Fig. 5**a. If $\Delta t$ tends to zero, Eq. (3) can be converted to an ordinary differential equation:

$$\frac{d\rho}{dt}=\frac{E(t)\cdot A}{V}-\frac{\alpha\cdot p}{V}\rho(t) \tag{4}$$

Through introducing boundary conditions and the values of relative parameters including $V$ =1 m$^3$, $A$ =1 m$^2$, $p$ =1 m$^3$/h, the Eq. (4) is solved and the $\rho(t)$ can be expressed as follows,

$$\rho(t)=E(t)+\left[\rho_0-E(t)\right]\cdot e^{-\alpha\cdot t} \tag{5}$$

where the $\rho_0$ is initial formaldehyde concentration at $t$ =0. Therefore, the value of correction factor $\alpha$ need to be determined for describing the formaldehyde emission characteristics $E(t)$ of each test group.

Test data from the background concentration tests were used to determine α in this study. For the background concentration test, the $E$(t) can be considered as the constant and taken as the background concentration $\rho_b$ after the test time $t$ larger than 48 hours, as mentioned above. Therefore, Eq. (5) is revised as follows,

$$\rho(t)=\rho_b+\left(\rho_0-\rho_b\right)\cdot e^{-\alpha\cdot t} \tag{6}$$

where $\rho_0$ and $\rho_b$ are taken as the average of twice background concentration tests, corresponding to 0.014 mg/m$^3$ and 0.0035 mg/m$^3$, respectively. Then, $\alpha$ is decided by fitting analysis and its value is taken as 0.06 in this investigation. The fitting curve is close to the test curves, as shown in **Fig. 5**a.

For the test groups in **Tab. 2**, the initial formaldehyde concentration $\rho_0$ is equal to 0, considering that the background concentration $\rho_b$ is removed from the test result of each group. Therefore, Eq. (5) is revised as Eq. (7) by introducing the values of $\alpha$ =0.06 derived from Eq. (6) and $\rho_0$ =0, as follows,

$$\rho(t)=E(t)\cdot\left(1-e^{-0.06t}\right) \tag{7}$$

Then, the $E(t_i)$, the formaldehyde emission at the $t_i$, can be calculated by substituting the corresponding test date of $\rho(t_i)$ into Eq. (7). For the proposed formaldehyde emission model described in Eq. (2), the parameters of $E_0$ and $k$ need to be determined for glubam board. A simple linear transformation is conducted on Eq. (2), and it is expressed as follows,

$$\ln E(t)=\ln E_0-kt \tag{8}$$

Based on the calculated results of $E(t_i)$ derived from the test data of $\rho(t_i)$ by Eq. (7), ln$E_0$ and $k$ can be determined by linear regression analysis, and the relative values of each group are also provided in **Tab. 3**.

**Table 3.** Test results of formaldehyde emission parameters.

| Group | $\rho_p$[a] (mg/m$^3$) Tested | $\rho_p$[a] (mg/m$^3$) Calculated | $E_0$[b] (mg/h/m$^2$) | $k$[c] （h$^{-1}$） | Remark |
|---|---|---|---|---|---|
| TNG-S1 | 0.0437 | 0.0419 | 0.0429 | $2.21\times10^{-4}$ | Standard test |
| TNG-S2 | 0.0416 | 0.0419 | 0.0429 | $2.21\times10^{-4}$ | Standard test |
| TNG-T1 | 0.0293 | 0.0278 | 0.0284 | $1.98\times10^{-4}$ | Low temperature |
| TNG-T2 | 0.0734 | 0.0707 | 0.0765 | $6.35\times10^{-4}$ | High temperature |
| TNG-R1 | 0.0351 | 0.0339 | 0.0344 | $1.26\times10^{-4}$ | Low relative humidity |
| TNG-R2 | 0.0489 | 0.0457 | 0.0471 | $2.83\times10^{-4}$ | High relative humidity |
| TNG-E1 | 0.0606 | 0.0588 | 0.0623 | $6.27\times10^{-4}$ | Unsealed edges |
| TNG-C1 | 0.0682 | 0.0661 | 0.0702 | $6.61\times10^{-4}$ | Bamboo decorative layer |
| TNG-C2 | 0.0859 | 0.0831 | 0.0889 | $7.50\times10^{-4}$ | Bamboo mat layer |
| TKG-S1 | 0.0806 | 0.0787 | 0.0846 | $8.12\times10^{-4}$ | Material type |

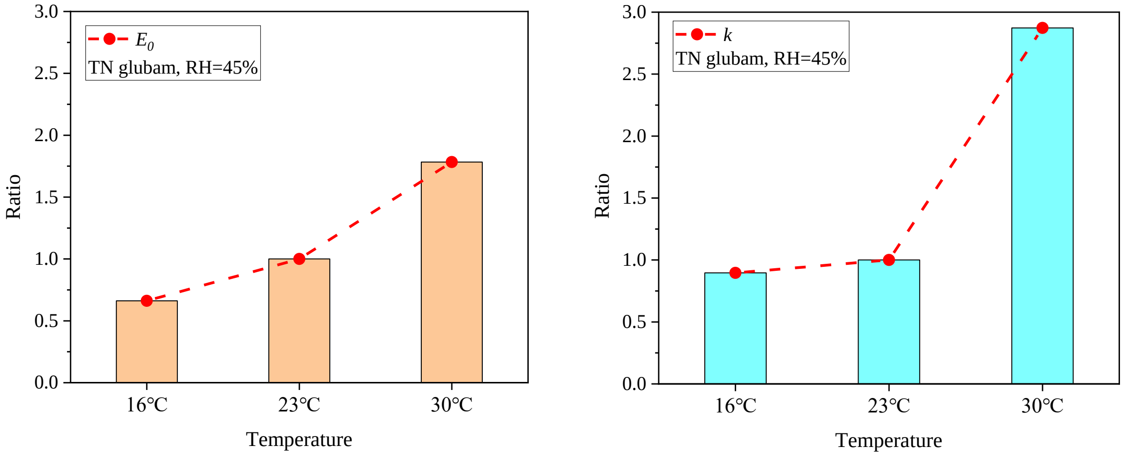
[a]Peak value of formaldehyde concentration in the climate chamber, [b]initial formaldehyde emission rate, [c]decay rate constant

The proposed formaldehyde emission model $E(t)$ for glubam board is validated by the test results. In this study, the formaldehyde concentration in the climate chamber $\rho(t)$ can be predicted based on Eq. (2), Eq. (7), and values of $E_0$ and $k$ in **Tab. 3**. The calculating curves are shown in **Fig. 5** as well as the test curves. It can be observed that the calculating curve can reasonably catch the peak value $\rho_p$ and the developing trend of the test curves under varied test conditions, meaning that the proposed formaldehyde emission model is acceptable within the test range.

On the other hand, comparison of the calculating and the test curves of the $\rho(t)$ also reveals that the proposed model overestimates the formaldehyde emission at the early stage of tests. This result suggests that the actual formaldehyde release from glubam board is more complex than the simple first-order decay model.

## 4 Discussions

For the proposed model expressed as Eq. (2), the parameters of the $E_0$ and $k$ are used to describe the formaldehyde release characteristics from glubam board under different test conditions. Based on the formaldehyde release process as mentioned above, it can be considered that the initial formaldehyde emission rate $E_0$ is mainly determined by the free formaldehyde content in glubam board and the volatilization capacity of formaldehyde through the gas-solid interface [34]. For the same samples, the free formaldehyde content can be considered as consistent. Therefore, the value of $E_0$ is actually decides the volatilization rate of the formaldehyde from the glubam surfaces. For the decay rate constant $k$, it actually reflects the formaldehyde concentration decay with the test time $t$ in the climate chamber, and its value depends on the diffusion rate of formaldehyde from inside to the surface of glubam board. So free formaldehyde content in glubam samples is lower as increasing the diffusion rate, and it causes a more significant amplitude reduction of formaldehyde emission from samples to air. Accordingly, the test concentration in the chamber $\rho(t)$ decreases relatively more obvious with test lasting. Influence of the experimental parameters on $E_0$ and $k$ of TN glubam are presented in **Figs. 7~9**, where the calculated results of the glubam standard test TNG-S1 are taken as 1.0.



(a) Comparison of $E_0$ (b) Comparison of $k$

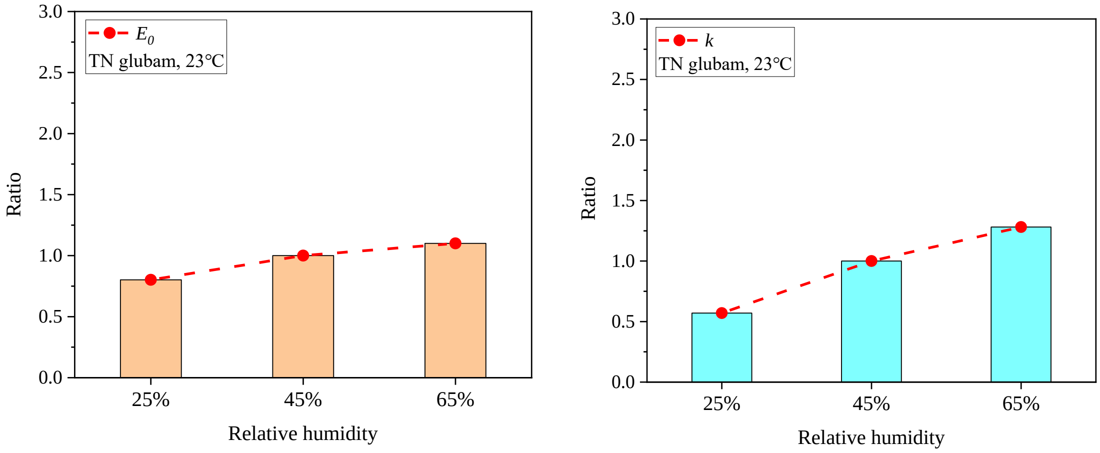
**Fig. 7.** Comparison of $E_0$ and $k$ of the temperature.

### 4.1 Effect of temperature

Comparison of $E_0$ and $k$ of the temperature series are shown in **Fig. 7**, including the TNG-S1, TNG-T1, and TNG-T2. It is found that the temperature has significant influence on formaldehyde emission characteristics. The $E_0$ accelerating increases with the temperature increase, implying that raising temperature significantly enhances the volatile capacity of the formaldehyde from glubam surface. The $k$ presents a similar increasing trend as the $E_0$. The formaldehyde is gaseous state at room temperature due to its low boiling point of -19.5 °C [19]. It is the fact that the diffusion ability of formaldehyde molecules depends on the thermal motion of molecules which closely relates to the temperature [35]. Therefore, the $E_0$ shows a substantial increase with the ambient temperature increases. Elevated temperature also causes the higher vapor pressure of free formaldehyde in glubam samples and enhances its interior transmission capacity. Therefore, more formaldehyde is released from the glubam boards in unit time which leads to more obvious decay of formaldehyde concentration $\rho$(t), as reflected in the increasing of the $k$.

### 4.2 Effect of relative humidity

Comparison of $E_0$ and $k$ of the relative humidity series are shown in **Fig. 8**, including the TNG-S1, TNG-R1, and TNG-R2. It reveals that both of two parameters exhibit a close increasing trend with the relative humidity increases. Formaldehyde has a certain hydrophilic property and can be soluble in water [36]. Increasing relative humidity, corresponding to relatively higher saturated vapor pressure in the climate chamber, promotes hydrogen bonding between formaldehyde molecules and water molecules and enhances the surface diffusion and inside transmission ability of the formaldehyde. Therefore, both of the $E_0$ and $k$ increase as increasing the relative humidity. However, the relative humidity shows an obviously smaller effect on formaldehyde emission compared with the temperature, suggesting that the temperature is the most important ambient condition for formaldehyde release from glubam board.



(a) Comparison of $E_0$

(b) Comparison of $k$

**Fig. 8.** Comparison of $E_0$ and $k$ of the relative humidity series.

### 4.3 Effect of edge treatment and covering material

**Figure 9** presents the comparison of $E_0$ and $k$ of four groups, in which TNG-S1 and TNG-E1 with different edge treatments correspond to sealed edges and unsealed edges, respectively. It can be seen that the $E_0$ and $k$ of TNG-E1 are much higher than those of TNG-S1, in which the $E_0$ and $k$ increase 45% and 184%, respectively. The results validate that sealing edges can significantly reduce the formaldehyde release from glubam board. As illustrated in **Fig. 3**, the edge corresponds to cutting plane of the glubam board, on which bamboo fiber ends are exposed to the air. As a type of fiber material, along the direction parallel to bamboo fiber is a shortcut to formaldehyde diffusion. Therefore, sealing edges not only reduces the surface area of glubam samples, but also, more importantly, blocks the shortcut for formaldehyde volatilization.

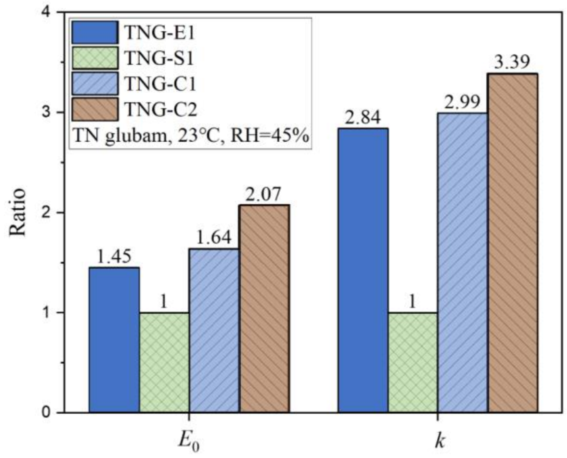


**Fig. 9.** Influence of edge treatment and covering material.

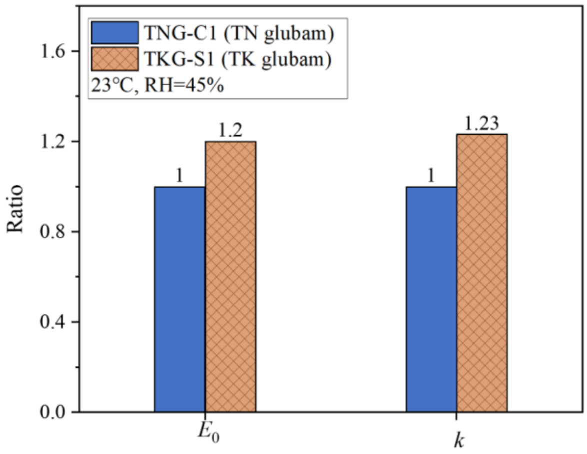


**Fig. 10.** Comparison of TN and TK glubam.

Comparison of TNG-S1, TNG-C1, and TNG-C2 in **Fig. 9** can quantify the influence of formaldehyde emission characteristics from glubam board with different covering materials. Compared with the TNG-S1 covered by waterproof material, the $E_0$ of the TNG-C1 and TNG-C2 are equal to 1.64 times and 2.07 times of the former, respectively, and the $k$ of the TNG-C1 and TNG-C2 are equal to 2.99 times and 3.39 times of the TNG-S1, respectively. It means that the formaldehyde release from glubam board covered by the bamboo-based decorative layer and bamboo mat is obviously easier compared with that covered by waterproof material. This result proves that the waterproof layers on the surfaces have excellent sealing property and effectively prevent formaldehyde diffusion through glubam surfaces. Therefore, reasonable selecting glubam with different surface layers according to application requirements is important and necessary for improving the indoor air quality of engineered bamboo buildings.

### 4.4 Effect of the type of engineered bamboo

The $E_0$ and $k$ of TNG-C1 and TKG-S1 were compared for revealing the difference in formaldehyde emission between the TN and TK glubam, considering that the TN glubam decorative board and the TK glubam have similar surfaces and could be directly exposed indoors as the decorative surface. It can be found in **Fig. 10** that the TN glubam exhibits relatively better indoor environmental friendliness than the TK glubam, in which the $E_0$ and $k$ of the former decrease about 20% and 23% compared with those of the latter, respectively. This result may be mainly attributed to the different resins used in the hot-press lamination process [37].

## 5 Conclusions

This study focused on formaldehyde emission characteristics from glubam board under different conditions, including the type of glubam, temperature, relative humidity, edge treatment, and surface covering condition. A series of formaldehyde concentration tests were performed by using 1 $m^3$ climate chamber. Based on the experimental results and discussions, the main conclusions can be drawn as follows:

(1) The peak value of formaldehyde emission from the thin-strip glubam (TN glubam) board under the standard test conditions is less than 50% of the upper limit ($0.124 mg/m^3$) in accordance with EN 717-1, and it can be classified as Class $E_1$ according to EN 13986. All test data under the non-standard test conditions with higher temperature and humidity are also lower than the upper limit within the test range.

(2) Based on the test data and a common first-order decay model, an analysis model was provided to estimate formaldehyde release from glubam board. The calculating curve from the proposed model can reasonably catch the main formaldehyde release characteristics including the peak value and the developing trend under varied test conditions. Therefore, the initial formaldehyde emission rate $E_0$ and the decay rate constant $k$ in the proposed model was used to analyze and discuss experimental parameters in this investigation.

(3) The test temperature and relative humidity has significant influence on the formaldehyde emission characteristics of glubam board, corresponding to the $E_0$ and $k$ shows an upward trend with the temperature or relative humidity increases. Comparatively speaking, however, the relative humidity shows a smaller effect.

(4) Sealing edges can significantly reduce the releasing rate of formaldehyde. Similarly, covering waterproof layer effectively prevents formaldehyde diffusion through glubam surfaces compared with glubam samples only with the bamboo strip mat cover or bamboo-based decorative layer, suggesting that reasonable selecting glubam with different surface layers according to application requirements is important for improving the indoor air quality of modern bamboo buildings.

The current study may be considered as the worst case for glubam in modern bamboo structures, considering that glubam is used as a type of standardized industrialized structural material with typically larger volume and relatively fewer surface areas and edge exposure, compared with the testing method based on the existing specifications for panel samples.

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## CRediT authorship contribution statement

**Bo Shan**: Conceptualization, Funding acquisition, Supervision, Investigation, Formal analysis, Writing – original draft. **Gang Wang**: Investigation, Formal analysis, Writing – original draft. **Panpan Lei**: Investigation. **Tianyu Li**: Supervision, Investigation. **Yan Xiao**: Supervision, Writing – review & editing. **Shujie Qin**: Investigation. **Jie Chen**: Investigation.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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