Effects of climatic conditions changes on crack growth

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Summary

For fracture caused by stress concentrations in beams, a crack is often at the origin of final rupture. When air humidity variations occur, the small area around the crack tip (process zone), under high stresses is also directly submitted to these variations, which generally decrease the strength of the beam. To emphasize this phenomenon, crack growth tests are carried out under opening mode along the grain direction on modified Tapered double Cantilever Beams. The tests are realised in a climate room allowing variations of relative humidity. It has been found that air-drying gives a high increase of the crack velocity while air wetting gives a smaller increase. The effects of natural climate variation on crack propagation and on time to failure of notched beams under constant loading are also studies. The phenomenon is modelling by non linear fracture mechanics assuming that only process zone is sensitive to fast variations of relative humidity. Correct trend of experiments is obtained.

1. Introduction

It is known from long time that failure of wood is influenced by creep rupture phenomena called in wood engineering as load duration effects (DOL) [1, 2]. As all other mechanical properties of wood, DOL effects depend on moisture content and more particularly depend on moisture content variations [3, 4, 5, 6]. The influence of the varying moisture content by the way of climatic conditions change is all the more important when the rupture is due to crack propagation. The present paper describes tests on the effect of relative humidity (RH) changes on crack growth [7, 8, 9]. Firstly, tests have been realised on modified Tapered Double Cantilever Beams specimens (mTDCB) (fig. 1), in mode I, under constant relative humidity and under sudden various changes of RH. Changes in crack velocity and time to failure were observed. Secondly, the effects of climatic conditions on the crack evolution and more precisely on time to failure of notched beams are presented.

A fracture mechanics model is developed considering the stability of a single crack in a viscoelastic orthotropic medium. The model allows getting correct predictions of the experimentally obtained values. Finally, the model is applied to duration of load experiments on LVL (Laminated Veneer Lumber) notched beams of under natural climate.

2. Experiments in opening mode

2.1 Test configurations

The chosen opening mode specimen, mTDCB, is submitted to a traction loading (fig. 1a). Tests have been realised on two materials: LVL (first test set) and Maritime pine (second test set). The choice of the specimen has been based on its special property allowing to a stable propagation of the crack: for crack length *a* lower than *w* (fig. 1), mTDCB displays a nearly constant K_I value (fig. 1b). So, crack growth and crack velocity will only be a function of viscoelastic properties of the material (and thus of the moisture content) and not of the instantaneous crack length.

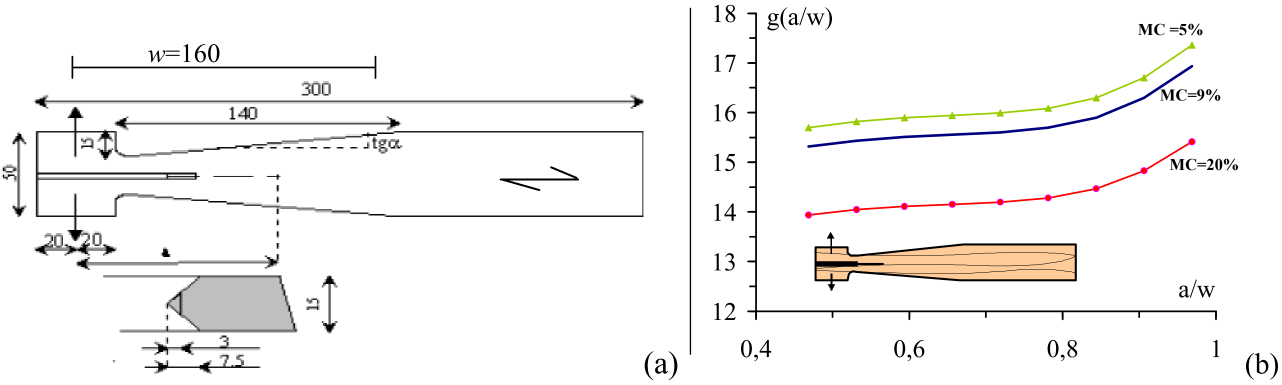

Fig 1 (a) Dimensions (mm) of the modified Tapered Double Cantilever Beam (in grey, the chevron crack tip). (b) Calibration function g for several moisture contents (MC): Stress Intensity Factor $K_I = \frac{F}{b\sqrt{w}} g\left(\frac{a}{w}\right)$ *(F: applied Load, b=thickness, w: characteristic dimension)*

During the first tests set on LVL mTDCB specimen, measurements of crack length have been made using a scale marked on each side of the specimen. In the second tests set on pine specimen, the crack length has been measured using a digital camera. The camera enables to follow the evolution of the crack on a face of the specimen. The lighting of the crack propagation zone has been ensured by a cold light source. The photographs have been acquired at regular time intervals with a program under the Labview software. The images are analyzed using traditional software of imagery to determine the crack length.

2.2 Experimental results

2.2.1 First test set

Tests have been realised on LVL mTDCB specimens in a climate box under ramp loading (at 0,01N/s) [7, 8]. Firstly, crack growth tests have been made under constant relative humidity (RH = 40%, 60% and 80%). The failure occurs in around 5 hours at RH=40% and 60% and in around 3 hours at RH=80%. The crack velocity at RH=40% is a bit higher than the crack velocity at 60%. At RH=80%, the crack propagation is slowly, twice slower than at RH=60%. Secondly, a rapid change in air humidity has been produced. The relative humidity shock has been realised after 2 hours loading for the tests beginning at the higher air humidity (RH=80%) and after 3 hours for all other tests. In spite of some scattering especially for RH=80%, an increase of crack velocity with moisture content is clearly observed [7] (fig. 6). Cyclic humidity changes have also been realised, the relative humidity has been kept quite constant (RH=60%) during 3 or 4 hours, and after every half an hour, RH increased or decreased of 20% (fig. 2). When air humidity change occurs, results show that an air-drying always increases the crack velocity unlike an air wetting which produces a decrease of velocity. Whatever the value of RH change, the amplitude of velocity increase seems clearly higher than the amplitude of the decrease. So, a drying appears to introduce more “damage” than a wetting.

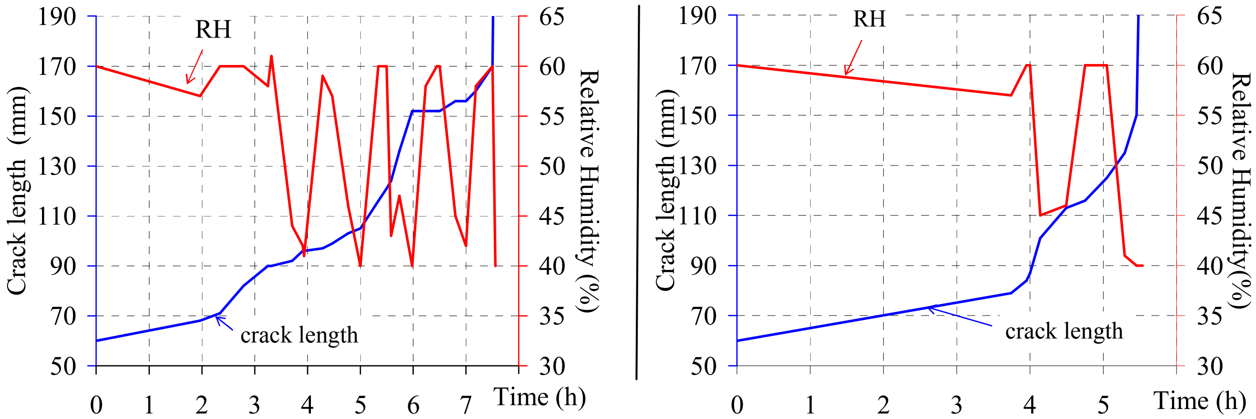

Fig 2 Crack length evolution under relative humidity (RH) change: LVL mTDCB under ramp load

An interpretation of this result can be proposed: the process zone is very sensitive to relative humidity variations because of its reduced size, so the moisture transfer time is very short. If tensile stresses exist in the process zone, a decrease of RH will shrink wood fibres, and stress increases. Maximum strength is exceeded and the crack propagation can be observed. On the other hand, if this same zone is under wetting, stress decreases, the fibres can lengthen and crack propagation needs a more important load level. In this case, the crack propagation becomes longer.

During these tests, the temperature during a RH shock could slightly change: the temperature increase when RH decreased and reciprocally. The measurement of the temperature has not been made during this tests thus, the change of the crack velocity is may be not due (only due) to RH evolution. Moisture content in wood depends on the relative humidity but also of the temperature, thus the behaviour of the specimen is also depending on the temperature. Temperature can also created additional stress concentration at the crack tip. Another remark concerning these tests: the load has been increasing during tests. To better determinate the influence of the RH and of the temperature on the crack evolution, new tests have been realised.

2.2.2 Second test set

Today, new equipments enable us to realised tests separate the effect of RH and of the temperature. For instant, only test with RH changes (temperature quite stable) have been realised and are presented in the next chapter. Tests are realised under a constant load thus, after a period of adaptation, the crack propagation can be supposed to be only due to climatic condition change.

Testing on Maritine pine specimens runs in two steps. Firstly, for given constant condition (temperature and RH), a dead load is applied to obtained a crack propagation of about 1 cm length. This load is kept constant during several hours without variation of the climatic conditions: the crack remains stable during this period. Secondly, a fast change of relative humidity is produced in about half an hour. The temperature and the load are not changed: a growth of the crack is generally observed. The figure 3a presents crack evolution for a variation of RH from 65 to 45 %: after stabilization of the crack, the change makes the crack to become unstable in a couple of hours.

Recent tests have been made to detect influence of cycle RH variation (fig. 3b). Temperature and load have been still constant and RH varies from 40 % to 80 %. At the beginning of the test, the crack regularly grows and velocity increases for each humidity changes, but the main effect is noticed after an increase of relative humidity. This result is opposite to preceding results and leads to think that the temperature change as also an influence on the crack propagation. This result must be confirmed by other tests.

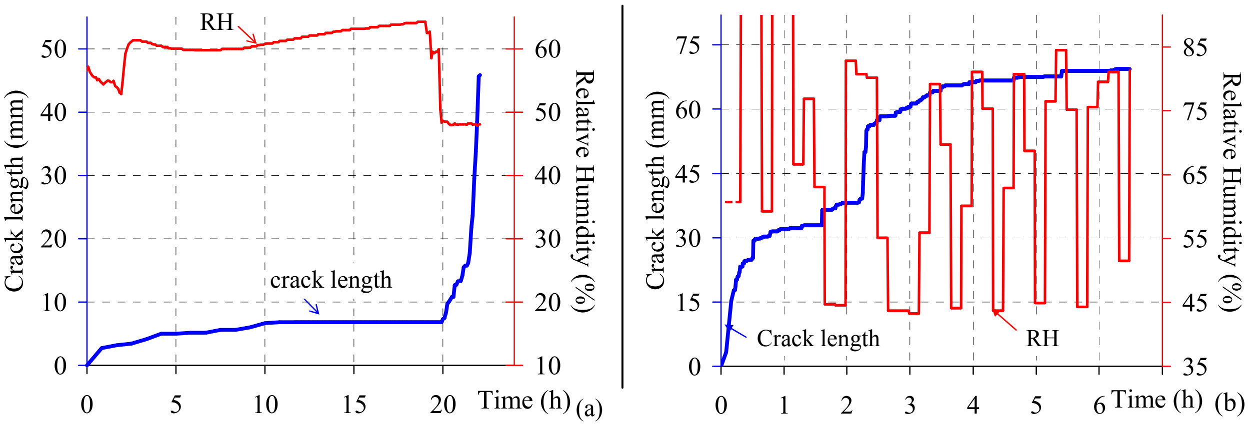

Fig 3 Crack length evolution under relative humidity (RH) change: pine mTDCB under dead load at constant temperature (T=25°)

3. Duration of load tests

All experimental details are given in [9]. A summary of the results is only given. The geometry of the LVL beams tested is indicated in figure 4. Duration of load tests have been carried out in open shelter natural climate for three months (one set by season). Tests were realized under constant loading or step by step loading [9, 10]. Here only constant loading is presented.

Correlation between drying period and failure period appears clearly in figure 4. Similar results were found by Schniewind [6] in tests on unnotched beams under cyclic relative humidity variations. On notched beams, we have found that the number of ruptures was higher just after an air humidity change in the beginning of the afternoon (between 3 pm and 4 pm) [9]. The figure 4 presents crack evolution of notched beams under dead load during 4 days: it appears that decreasing RH increases the crack velocity. However some changes in temperature exist but the effect of the temperature is considered smaller to influence the time to failure and it will be not taking into account in the modelling.

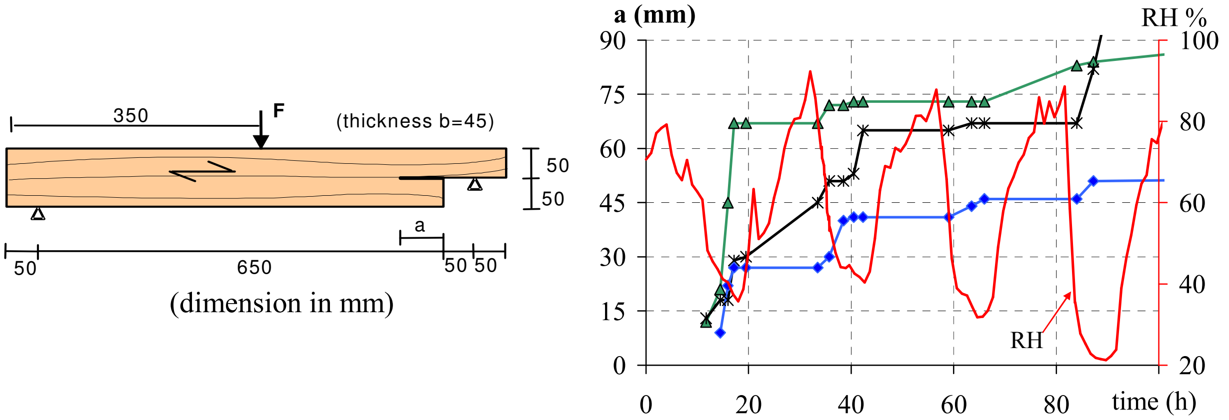

Fig 4 Crack length (a) evolution under various relative humidity (RH):LVL notched beams under dead load

Longest propagation times are found for dry and getting dry seasons. If crack appears during wetting period (autumn) (fig. 7), a massive water transfer appears through the crack tip [11]. These water transfers should cause the acceleration of the crack growth. In the same way, this can explain the propagation time found in winter. When rupture occurs in winter, the relative humidity and the moisture content are high (beams were conditioned during autumn, a wet period). Water transfer kinetics on the crack tip appears the most important parameter for the crack propagation speed and therefore the duration of load of cracked beams. The experimental results, stress level SL against time are given in the next chapter.

4. Theoretical approach of environmental effects

The proposed crack model is based on the assumption of a process zone located at the crack tip. This process zone is highly damaged and contains a distribution of cohesive stresses. When air humidity variations occur, the properties of this small area vary very quickly. On the opposite, the properties of the bulk material, following water transfer laws vary more slowly.

4.1 Viscoelastic Crack model (VCM)

The material containing the crack is assumed to have viscoelastic and orthotropic properties [12]. These properties are assumed to depend on the average moisture content. A distribution of cohesive stress σ_c in the damage zone exists but is not necessarily uniform as in the Dugdale model reference. For simplification, it will be assumed hereafter to vary linearly.

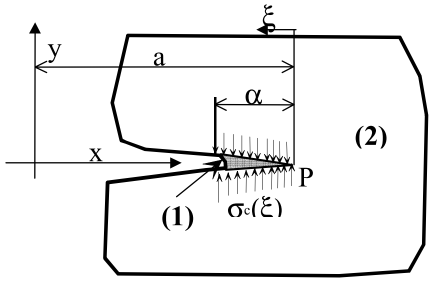

Fig 5 Cohesive crack model (1): Damage area of length α (with non-linear viscosity) (2): Bulk material (linearly viscoelastic)

With the notations of figure 1 the Schapery [12] formalism leads to:

$$K_I = \sqrt{\frac{2}{\pi}} \cdot \int_0^{\alpha} \frac{\sigma_c(\xi)}{\sqrt{\xi}} d\xi = \sqrt{\frac{2\alpha}{\pi}} \cdot \sigma_m I_1 \qquad [1]$$

with $I_1 = \int_0^{\alpha} \left[\frac{\sigma_c(\xi)}{\sigma_m} \frac{1}{\sqrt{\alpha.\xi}} \right] d\xi$ and $\sigma_m = \underset{0<\xi<\alpha}{Max}(\sigma_c(x))$

K_I is the Stress Intensity Factor depending on the geometry of the structure and crack length and on the elastic property of the material (if it is not isotropic). For orthotropic viscoelastic medium containing a crack along a material axis (longitudinal direction hereafter), a relation between stress intensity factor K_I and the fracture energy G_{FI} has been established:

$$2G_{FI} = \kappa_{22}^{v} \left(\frac{\lambda_n^{1/n} \alpha}{\dot{a}} \right) . K_I^2 \qquad [2]$$

where $\dot{a}$ is the crack velocity; κ_{22}^{v} is a reduced creep compliance in mode I along a natural axis.). In plane stress, using a quasi-elastic method, at each instant t, $\kappa_{22}^{v}(t)$=2/E*(t) with E* is the equivalent orthotropic stiffness. The parameter λ_n is depending on n [8, 12].

The reduced creep compliance in mode I, κ_{22}^{v} can be assumed to be represented by a power law:

$$\kappa_{22}^{v}(t) = A_o + A_2.t^n \qquad [3]$$

A_o, A_2 and n are material parameters.

The creep compliance (Eq. [3]), with the equation [2], gives a useful form of the crack velocity:

$$\frac{da}{dt} = \frac{\pi}{2}\left[\frac{A_2\lambda_n}{A_o\left(K_{Ic}^2 - K_I^2\right)}\right]^{1/n} \frac{K_I^{2(1+1/n)}}{(\sigma_m I_1)^2} \qquad [4]$$

with $K_{Ic} = \sqrt{2G_{FI} / A_o}$ is the critical stress intensity factor

Equation [4] shows clearly that the velocity becomes unbounded when K_I approaches K_{Ic} from below; so failure is obtained when K_I=K_{Ic}. K_I of specimen are obtained by finite element calculation for several moisture contents introducing a calibration function (fig. 1b). Viscoelastic stiffness was obtained from tension tests. From the experimental results, values of the parameters needed into relation [4] were obtained for three constant relative humidity. They are given in table 1 for LVL specimens.

RH (%)	MC %	A_o [MPa^{-1}]	A_2 [MPa^{-1}s^{-n}]	n	λ_n	σ_m [MPa]	I_1	K_{Ic} [MPa√mm]
40	5%	0,002	6,5E-4	0,43	0,628	50	4/3	25,1
60	9%	0,0023	7,0E-4	0,40	0,645	50	4/3	24,8
80	20%	0,0032	8,0E-4	0,37	0,664	42,5	4/3	20,9

Table 1 Values of experimental parameters for LVL specimens used in the fracture mechanics model

When relative humidity variation occurs, these parameters are assumed to vary linearly in function of RH except for the parameter σ_m and I_1. When air humidity changes quickly, RH velocity must be taken into account. For short term tests, this viscosity is supposed to influence only the cohesive stress in the damage zone. So, the resultant of the cohesive stress in the damage area is replaced by:

$$\sigma_m I_1(RH, \overset{o}{RH}) = \sigma_m I_1(RH) * \left[1 + k.\overset{o}{RH}\right] \qquad [5]$$

k is an adjustment factor and the derivative of air humidity with time. k takes the empirical value 45 when RH decreases and the value 60 when RH increases.

4.2 Application to rapid air change on mTDCB

The computed crack velocities are given in figure 6, which contains average of experimental values too. It appears that the crack velocity is highly increased when RH decreases from 80% to 40%. A similar slope is obtained from 60% to 40%. On the opposite, the increase in air humidity produces only small decrease of velocity. The calculations show that this decrease does not seem to depend on the value of the initial RH as in the previous case. As relative humidity change quickly, the expression of K_I used in the model is the one obtained whith the moiture content at the beginning of the test.

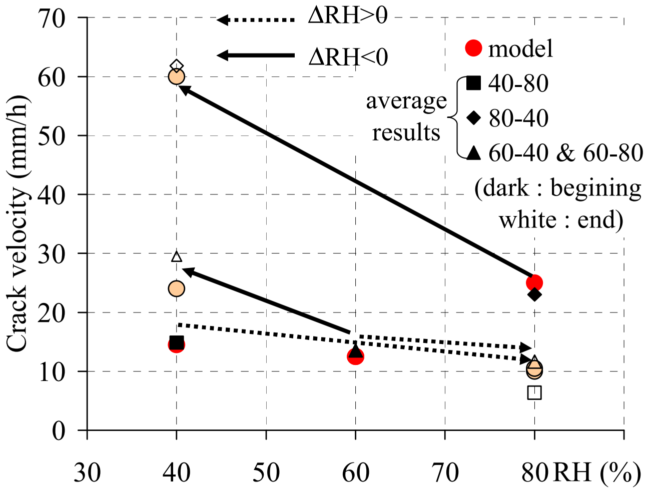

Fig 6 Crack velocity function of air humidity change: experimental points and predicted curves

4.3 Application to notched beams under constant and climatic conditions

Figure 7 displays observed failure times of notched beams under dead load. The values of Stress Level SL are corrected estimate using a ranking method. In this study, SL is equal to the ratio of the applied load and of the estimated strength of beam at a moisture content of 9% (RH=60%). The results obtained during four seasons and in a conditioning room (at RH 60% and at RH=80%) are illustrated in figure 7. Computations are made with values of the parameters given in table 1. Constant relative humidity and also cyclic variation between RH=40% and 80% with a 24 hours period was modelling.

Despite the usual scattering of experimental results, it appears that the model give a correct trend of the duration of load effect. However, estimations are slightly over conservative and predictions in cyclic RH fall near the predictions found for the higher constant RH.

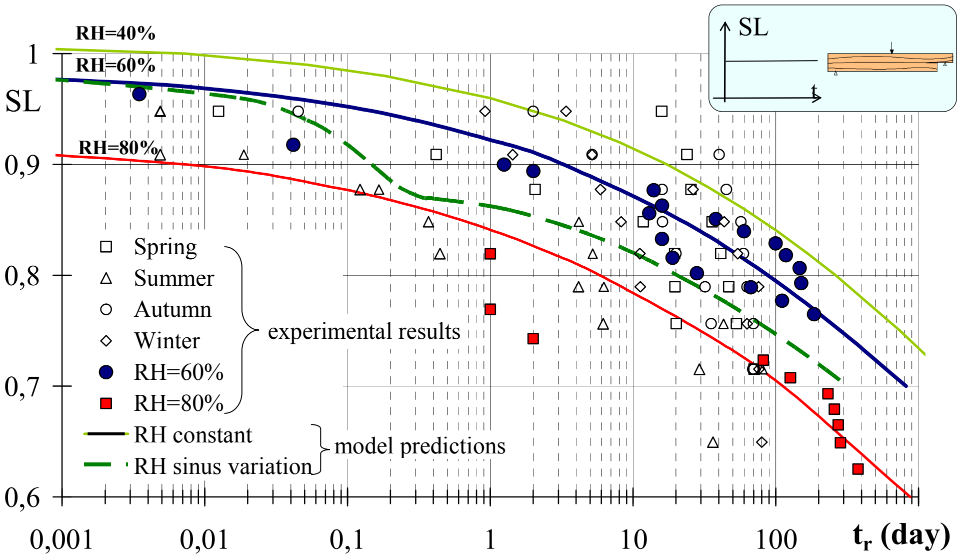

Fig 7 Duration of load of LVL notched beams under climatic conditions (four seasons) and under constant relative humidity RH: experiments and prediction of the fracture mechanics model (VCM) (RH sinus variation between 40% and 80% in 24 hours, beginning RH=60%)

5. Conclusions

Interpretation of experimental results obtained on notched beams in bending under natural climate has been proposed. It was observed a higher probability of fracture during drying period than during the wetting one. Failure is assumed to be represented by a crack growth model in a viscoelastic material. The cohesive stress distribution in the damaged zone is assumed to depend on the instantaneous relative humidity change. The model has been calibrated from tests on mTDCB specimens firstly under constant relative humidity and secondly under sudden air drying or air wetting. Calculations show that the sudden RH change produces a rapid change of the crack velocity. The increase of crack velocity during drying period is higher than the reduction in velocity during wetting period. Application to bending tests on structural notched beams under natural climate allows predicting the changes of duration of load effect experimentally obtained.
A point not study in this paper is the effect of the temperature on the crack propagation: this is the object of futures tests and modelling.

6. References

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