FURTHER EXPERIMENTS ON CREEP-RUPTURE LIFE UNDER CYCLIC ENVIRONMENTAL CONDITIONS[1]

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ABSTRACT

An increase in beam size from 10 by 20 mm to 2 by 2 inches increased the mean time to failure at a load level of 70% of modulus of rupture of specimens subjected to moisture content cycling by more than one order of magnitude. The effect of temperature cycling appears to depend on moisture content. The results indicate that the present load duration factor for wood is adequate under normal conditions, but that adjustments are needed when loaded members are small or when there are severe cyclic changes in ambient conditions.

Additional keywords: *Pseudotsuga menziesii*, elastic properties, creep rupture strength, load duration factor, moisture content, temperature.

This is a continuation of a previous study (Schniewind 1967), where it was found that cyclic changes in equilibrium moisture content conditions caused significant reductions in time-to-failure of beams under constant load. Most of the work was done at constant temperature and a load level of 70% of static modulus of rupture. Under these conditions, time-to-failure depended on the amplitude in the average moisture content reached by the beams during cycling. A few experiments that included cyclic changes in temperature between 60 and 90 F indicated that, in this range, temperature affected creep-rupture life only indirectly to the extent that it determined the amplitude of variations in average beam moisture content.

One objective of the present experiments was to confirm findings regarding the effect of temperature by using a more adequate number of replications. The main purpose, however, was to investigate the effect of specimen size. The previous experiments were made with beams 10 × 20 mm in cross section. Published reports of premature failure of specimens during creep studies under changing moisture conditions all involved equally small or smaller beams (Hearmon and Paton 1964; Raczkowski 1969; Bethe 1969). Since reduction in creep-rupture life was found to be proportional to the amplitude of cyclic variations in average moisture content (Schniewind 1967), it might be expected that with increasing size a smaller portion of the total cross section would be subject to significant moisture content changes. For beams of sufficiently large size, moisture content changes would then become confined to the surface layers so that changes in average moisture content would become extremely small. As a result, the effect of cyclic environmental changes on creep-rupture life (i.e., on the load duration factor) could also be expected to be minor.

MATERIAL AND METHODS

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was used for the experiments. Two sizes of simply supported, center-loaded beams were tested. The smaller beams were 1 cm deep, 2 cm wide, with a span of 20 cm. The larger beams were 2 × 2 inches in cross section with a span of 40 inches, so that the span-depth ratio of both types of beams was the same.

All specimens were loaded to produce an extreme fiber-stress equal to 70% of the static modulus of rupture. For each small specimen, modulus of rupture was estimated from measurement of the dynamic

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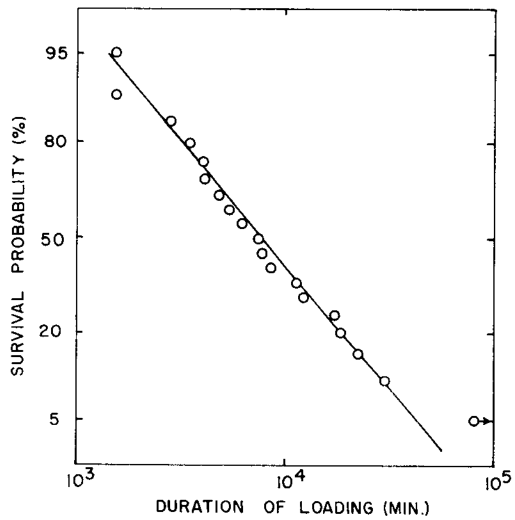

FIG. 1. Survival probability vs. duration of loading for small specimens at 70% load level subjected to Type D cycling (temperature cycling with major moisture changes).

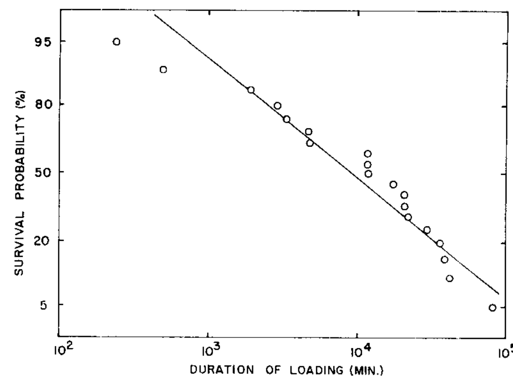

FIG. 2. Survival probability vs. duration of loading for small specimens at 70% load level subjected to Type E cycling (temperature cycling with minor moisture changes).

modulus of elasticity and specimen weight, using a previously determined regression equation (Schniewind 1967). For each large specimen, modulus of rupture was estimated from the result of a static test made on an end-matched control specimen. Control tests were made at room temperature and a nominal moisture content of 12%. The static test was made at a testing speed of 0.2 inch per minute (giving equivalent strain rate to that used for small specimens), using the same beam geometry as for the creep-rupture tests.

Testing equipment was essentially the same as that used for earlier tests (Schniewind 1967), except that beam deflections and weight of control specimens were recorded continuously. All tests were made inside a programmable humidity cabinet equipped with time meters to detect specimen failure. The smaller specimens were loaded in frames with a lever system. The larger specimens were loaded in an inverted position so that the "center load" acted upward and the reactions downward. One reaction was fixed, the loading head was essentially fixed but connected to a jack to allow periodic adjustment to a horizontal position, and the second reaction was loaded with dead weights, thus allowing the use of dead loading with only half the weight required for the conventional arrangement. The moisture-content controls for the larger specimens consisted of end-matched sections 6 inches long. Beams and controls were end-coated to restrict moisture movement to the side grain.

Types of cyclic environmental conditions used in this study are shown in Table 1. Thirteen small specimens were tested under Type D and fifteen under Type E cycling, so that in combination with the previous results the total number of tests in each group would be 19. Nineteen larger specimens (2×2 inch) were tested under Type A cycling, for comparison with results of small specimens under identical cycling already reported by Schniewind (1967).

RESULTS AND DISCUSSION

Temperature cycling of small specimens

Figure 1 shows results of tests under Type D cycling. One specimen had not failed after some 80,000 min, at which time the test was discontinued. All other points are grouped closely around a straight line in the normal probability plot of Fig. 1, showing that the logarithms of the times-to-failure are normally distributed. The aver-

TABLE 1. *Types of cyclic environmental conditions*

Type of cycling	Temperature minimum °F	Temperature maximum °F	Temperature functional form	Relative Humidity minimum %	Relative Humidity maximum %	Relative Humidity functional form	Period hrs.
A	75	75	constant	35	87	square wave	24
D	60	90	sinusoidal[1]	35	87	sinusoidal[1]	24
E	60	90	sinusoidal[2]	65	68	special[2]	24

[1] The temperature and relative humidity functions were 180° out of phase, i.e., the point of maximum temperature and minimum relative humidity coincided.

[2] The relative humidity was varied in such a way that the nominal equilibrium moisture content conditions remained constant.

age time-to-failure was computed using the method of the censored distribution (Hald 1952). This method makes it possible to estimate population parameters from a sample when some observations are only specified to the extent that they are equal to or larger than a certain value. In this particular case, one out of the 19 values of time-to-failure could be specified only as being equal to or larger than the time at which the test was discontinued.

The estimate of average time-to-failure was 7950 min, nearly the same as the previous estimate of 8170 min based on only 6 specimens. Eight specimens failed during the second half of the cycle when temperature was below average and RH (relative humidity) was high; ten failed while the temperature was high and RH was low. This shows that surface conditions at the moment of failure were not an important factor.

Figure 2 shows results of Type E cycling. Although specimens were intended to remain at the same nominal equilibrium moisture content condition throughout the cycle, small moisture content changes did occur. Distribution of the points is more irregular than those for Type D cycling but can still be considered approximating the normal distribution.

The average time-to-failure, based on logarithms, was only 9111 min, not much longer than for Type D cycling. This is considerably less than the initial estimate based on only four specimens (Schniewind 1967), and shows that results from just a few tests can be very misleading.

Results of Type D cycling indicate that temperature cycling has little or no effect on time-to-failure, since the average is about what would be expected on the basis of the concurrent moisture content changes alone. For Type E cycling this is not the case, since moisture content changes were very small at an amplitude of 0.32%. This suggests that there is a temperature-moisture content interaction. In Type D cycling high temperature always coincides with low moisture content, and high moisture content occurs only at low temperature. In Type E cycling, however, moisture content remains nearly constant and thus is relatively much higher during the high temperature part of the cycle. Supporting the hypothesis of a temperature-moisture content interaction is the observation that all but one of the 19 specimens in Type E cycling failed during the first or second quarter of the cycle, when temperature is above the mean—in fact, 14 of the 19 specimens failed when the temperature was within 3 degrees of maximum (i.e., at temperatures between 87 and 90 F).

Since moisture content changes were minimal and temperature changes occur at

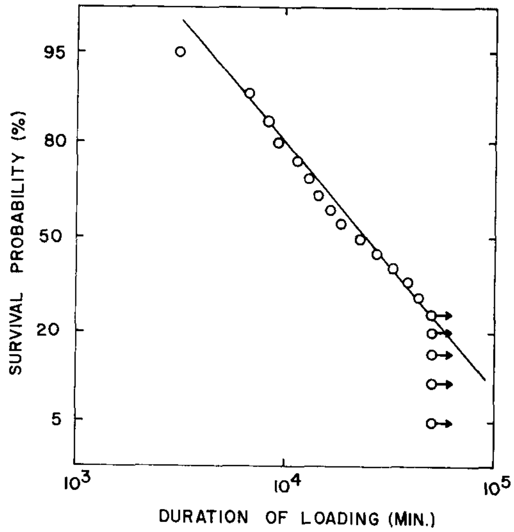

FIG. 3. Survival probability vs. duration of loading for large specimens at 70% load level subjected to Type A cycling (large moisture changes at constant temperature).

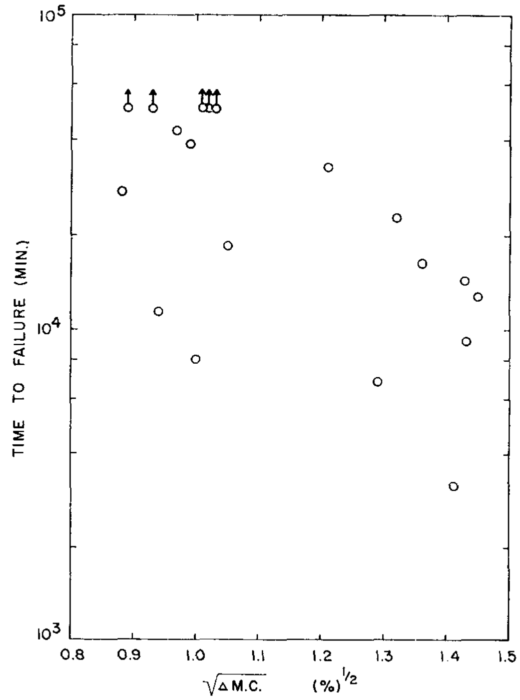

FIG. 4. Time to failure of large specimens as a function of the square root of the moisture content amplitude.

much more rapid rates than do moisture content changes, temperature and moisture content gradients cannot be expected to be a major factor in Type E cycling. Temperature level under constant conditions can be expected as a factor (Bach and Pentoney 1968), but except in the case of highly nonlinear (in temperature) effects, each increment of time at elevated temperature would tend to be compensated by an equal increment at decreased temperature. Hence, cycling as such must have an effect provided that moisture content is sufficiently high. Temperature changes have been found to have an effect on creep (Kitahara and Yukawa 1964; Schniewind 1966; Arima 1972) and thus can also be expected to affect creep-rupture life.

Relative humidity cycling with larger specimens

Since it was possible to test only one larger specimen at a time, it became very important to make the testing as efficient as possible. It became apparent immediately that the larger specimens would require much longer time to failure than the smaller specimens previously tested (Schniewind 1967) under the same conditions. Accordingly, a truncation point of 50,000 min (approximately 5 weeks) was selected somewhat arbitrarily. This proved to be a reasonable choice. Of the 19 specimens tested, 14 failed within 50,000 min. The remaining five were discontinued at the truncation point.

Figure 3 shows the results. Plotted points of specimens that did fail are closely grouped about a straight line, again indicating normal distribution of the logarithms of time-to-failure. The estimated mean calculated from the censored distribution is 24,400 min, considerably greater than the average of 1445 min previously obtained for small specimens under the same type of cycling (Schniewind 1967). On the other hand, this is still less than the nearly 100,000 min obtained by Youngs and Hilbrand (1963) at the same load level under constant RH conditions, or the 71,000 min cal-

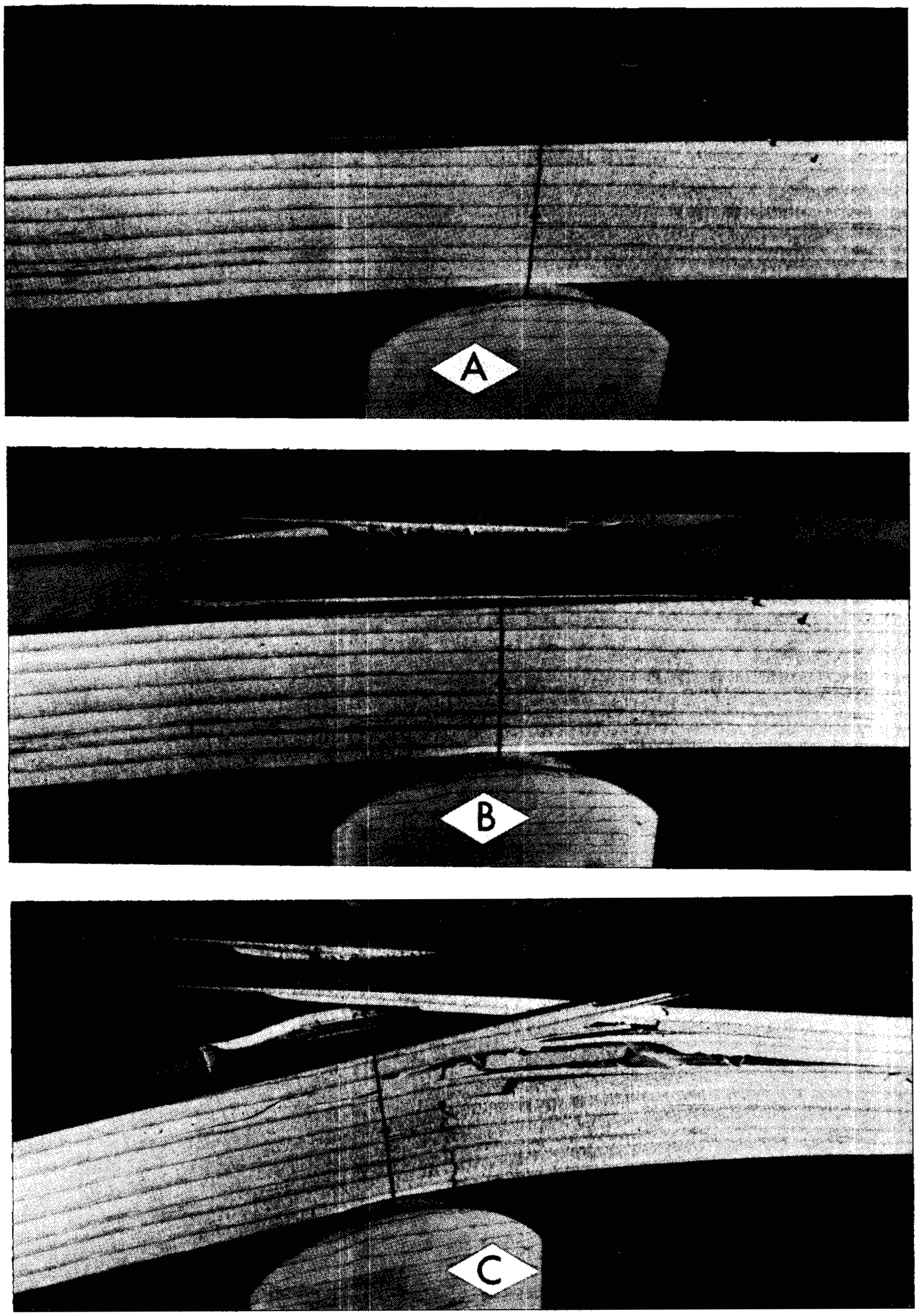

FIG. 5. Stages of tensile failure in specimen 112. First indication of tensile failure was observed at 5288 min. The failure is shown extending across entire tensile face at 8313 min (a); it has become deeper at 9442 min (b); and the final failure occurred at 12,912 min (c).

culated from a regression equation combining results of several studies (Pearson 1972).

Although loading of large specimens was constant at 70% of modulus of rupture based on static tests of matched controls, there was some correlation between time-to-failure and the absolute value of modulus of rupture. This was surprising until it was found that specific gravity differences provided a reasonable explanation. Specific gravity is correlated not only with modulus of rupture, but also with moisture diffusion coefficient (Siau 1971). As a result, moisture content changes are greater in low-strength, low-density specimens. As shown previously (Schniewind 1967), time-to-failure under cyclic conditions depends on the amplitude of moisture content changes. Figure 4 shows time-to-failure values plotted as a function of amplitude of the moisture content change. Although numerical evaluation of the data cannot be made because some tests were discontinued, there is an unmistakable trend to shorter times-to-failure with increasing amplitude of moisture content change.

Five of the 14 specimens that failed did so during the low RH part of the cycle, thus paralleling previous findings with smaller specimens. Few of the specimens failed without prior visual evidence of partial failure, usually in tension and usually well in advance of final failure. Several specimens showed substantial tension failures extending across the entire tension face, and yet continued to carry the full load for as long as 8.5 days. Figure 5 shows several stages of tensile failure in one such specimen.

The average amplitude of moisture content variations in the larger specimens was 1.4%. As expected, this is much less than the 6.6% previously found for smaller specimens under the same type of cycling. Two extra control specimens were subjected to Type A cycling for 10 cycles: one was taken out at the end of the low RH part of the cycle, and the other at the end of the high RH part. Two sections were then cut from each specimen and these in turn were cut into a shell, intermediate zone, and core (dividing the half-thickness into three approximately equal parts). Results showed that the moisture content of the core and intermediate zone remained unchanged during cycling, the only measurable changes taking place in the shell. The moisture content amplitude in the shell was 2%, as compared to an over-all average amplitude of 0.9%.

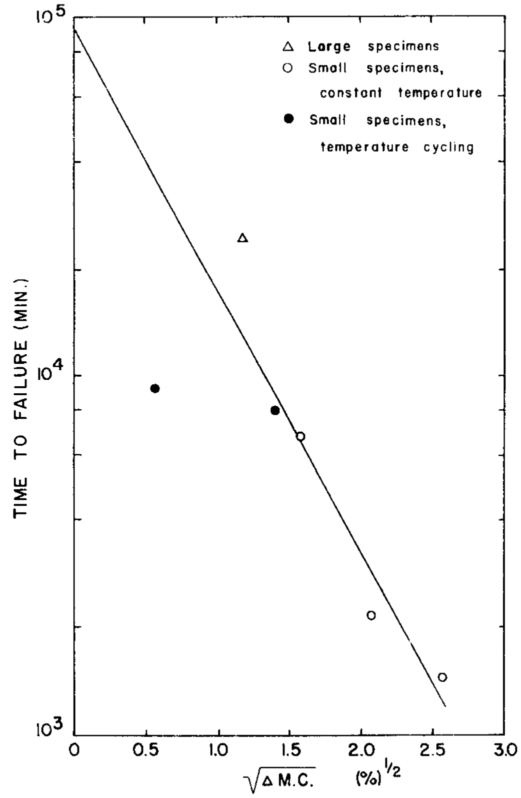

FIG. 6. Mean time to failure, combining results of the present and a previous study, as a function of square root of moisture content amplitude. The (freehand) trend line intersects the time to failure axis at the mean failure time (70% load level) obtained by Youngs and Hilbrand (1963) under constant conditions.

The reduced effect of RH cycling on larger specimens was also evident in the deflection pattern. Most specimens showed a net increase in deflection during the adsorption cycle, recovery being either slight and temporary or absent entirely, but there was always at least a reduction in creep rate. Small specimens, in contrast, showed more definite changes in deflection during adsorption. Some large specimens showed a slight net decrease in deflection during adsorption, and this was confined to specimens with the longest times-to-failure. In either case, changes in deflection due to cycling were small compared to total deflection, resulting in nearly smooth creep curves with only slight undulations. Neglecting the undulations, the curves followed the classical pattern of primary, secondary, and tertiary creep.

Moisture-content amplitude as the common factor

Previous results indicated that for smaller specimens, the time-to-failure at 70% load level depended on the amplitude of the cyclic variations in average moisture content produced by cyclic changes in the environment (Schniewind 1967). Data from a variety of environmental regimes could be combined in a single plot that showed a linear relationship between the logarithm of time-to-failure and the logarithm of moisture content amplitude. In attempting to combine the previous results with the results reported here, it was found that results from larger specimens could be included with results from smaller specimens (cf. also Fig. 4) in a similar plot. It was also found that a better over-all fit of the data was obtained by using the square root rather than the logarithm of moisture content amplitude. Figure 6 shows the result.

Figure 6 shows that test averages for smaller specimens at constant temperature are close to a straight line passing through the appropriate time-to-failure value at zero moisture content change (test value at constant conditions). For the smaller specimens subjected to temperature variations, the point deriving from the more realistic Type D tests falls nearly on the line, but the point from Type E tests deviates considerably, probably for reasons already discussed. The point for 2- × 2-inch specimens falls in an intermediate position, which is not surprising since width-to-depth ratio is not the same in smaller and larger specimens. Nevertheless, the overall trend of the data can be represented by a single line as shown.

PRACTICAL IMPLICATIONS FOR THE LOAD DURATION FACTOR

The results of this study have shown that size does indeed determine to what extent cyclic variations in environmental conditions affect time-to-failure. Average time-to-failure increased by more than one order of magnitude following the increase in beam cross section from 1 × 2 cm to 2 × 2 inches, but was still short of the average time-to-failure recorded at the same load level under constant environmental conditions. Since much structural lumber is in fact 1.5 inch in actual thickness, the question arises whether the load duration factor used in deriving working stresses that has been obtained from tests under constant moisture content conditions can be considered as adequate.

Several factors must be considered in attempting to answer that question. One of these is beam geometry. A 2 × 12 loaded as a plank would probably perform about the same as a 2 × 2, since the absolute as well as the relative penetration of moisture from the tensile and compressive faces is about the same. In a 2 × 12 loaded on edge, however, relative penetration from the tensile and compressive faces is much less. This would probably lead to an increase in time-to-failure for most structural applications. Another factor is the type of cycling that occurs. The Type A cycling used in these studies is probably much more severe than the variations encountered in use. Even Type D cycling includes much more variation in temperature and RH than would be expected in use on a sustained basis. Since the difference in average time-to-failure between Type D and Type A cycling for the smaller specimens was considerable, an estimate was made how this would affect results with 2- × 2-inch specimens. Some moisture content control specimens were subjected to Type D cycling and the moisture content amplitude was determined. The average time-to-failure was then estimated from Fig. 6 as 34,500 min. Additional reduction in severity of the type of cycling would undoubtedly bring the average time-to-failure even closer to the value obtained under constant conditions.

We may conclude that severe cyclic changes in environmental conditions can cause serious reductions in the creep-rupture life of small specimens. As specimen size increases and severity of environmental changes decreases, creep-rupture life approaches that obtained with specimens at constant moisture content. Under normal conditions, the load duration factor presently used (ASTM 1972) therefore seems adequate. However, in special cases where critically stressed members are small or subjected to unusually severe cyclic environmental changes, an adjustment of the load-duration factor would be advisable.

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