

TEMPERATURE CHANGE GENERATED LONGITUDINAL FRACTURE OF INHOMOGENEOUS BARS WITH FIXED SUPPORTS

PODUŽNI LOM NEHOMOGENIH ŠTAPOVA SA NEPOKRETNIM OSLONCIMA IZAZVAN PROMENOM TEMPERATURE

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Keywords

- continuously inhomogeneous bar
- fixed supports
- longitudinal fracture
- temperature change
- analysis

Abstract

Continuously inhomogeneous structural materials are characterised by smooth change of their properties in a solid. The most typical examples in this relation are the functionally graded materials that have a quickly growing use in a variety of structural applications in up-to-date engineering. In many cases different continuously inhomogeneous structural members are subjected to temperature change that may have significant influence on structural integrity. This paper aims to clarify how the longitudinal fracture of continuously inhomogeneous bars with fixed supports is affected by temperature change. In particular, we consider a bar with circular cross-section. The bar has two portions with different radius. Besides, the bar hosts a longitudinal crack representing a circular cylindrical surface. Due to the fact that the bar is statically indeterminate structure (both supports of the bar are fixed), the temperature change to which the bar is subjected induces stresses that have influence on longitudinal fracture. The problem of strain energy release rate (SERR) in the bar is solved. An approach from the literature is used for checking. Since the bar has non-linear elastic behaviour under temperature change, the complementary strain energy is used for deriving SERR. A variety of graphs revealing the influence of temperature change and other bar model parameters on SERR are presented.

INTRODUCTION

Continuously inhomogeneous structural materials which are mixtures of two or more constituent materials exhibit remarkable mechanical, thermal and fracture properties that are significantly superior to the homogeneous materials from which they are produced [1-3]. Compared to fibrous composites, continuously inhomogeneous structural materials are also superior, mainly due to the smoothly changing microstructure, which reduces stress concentrations, thereby improving the failure behaviour and increasing the load-bearing capacity of structures [4, 5]. Rapid progress in the field of continuously inhomogeneous materials offers excellent opportunities for tailoring the change of microstructure along specific directions in the solid in order to produce materials

Ključne reči

- kontinualno nehomogen štap
- nepokretni oslonci
- podužni lom
- promena temperature
- analiza

Izvod

Kontinuirano nehomogeni konstrukcioni materijali karakterišu se neprekidnim promenama svojstava u čvrstom stanju. Najtipičniji primeri ovog tipa su funkcionalni kompozitni materijali sa brzo rastućom primenom u raznim savremenim inženjerskim konstrukcijama. U mnogim slučajevima, razni kontinuirano nehomogeni konstrukcijski elementi su izloženi promenama temperature, koje mogu imati značajan uticaj na integritet konstrukcije. Cilj ovog rada je da se razjasni kako promena temperature utiče na podužni lom kontinuirano nehomogenih štapova sa nepokretnim osloncima. Posebno razmatramo štap kružnog poprečnog preseka. Štap ima dva dela različitog poluprečnika. Pored toga, štap ima podužnu prslinu predstavljena kao kružna cilindrična površina. Zbog činjenice da je štap statički neodređen (oba oslonca štapa su nepokretni), promena temperature kojom je štap izložen izaziva napone koji utiču na podužni lom. Rešava se problem brzine oslobađanja energije deformacije (SERR) u štapu. Za proveru se koristi pristup iz literature. Pošto štap ima nelinearno elastično ponašanje sa promenom temperature, za izvođenje SERR se koristi komplementarna energija deformacije. Daje se niz dijagrama koji pokazuju uticaj promene temperature i drugih parametara modela štapa na SERR.

with predetermined properties, [6-9]. All these advantages make continuously inhomogeneous structural materials with great potential to replace homogeneous metals and traditional fibrous composites in numerous industries.

In recent decades, continuously inhomogeneous materials, including functionally graded ones, have emerged as a cornerstone technology in many sectors of up-to-date engineering where various structural members operate under temperature changes. The wide use of continuously inhomogeneous (functionally graded) materials represents an essential strategy for qualitatively improving the performance of engineering structures subjected to heavy loads including temperature fields. There are many issues related to failure behaviour and fracture of these structures that are far from

finding their satisfactory solution. Consequently, analysis of different aspects of failure is crucial for assessing the integrity and safety of continuously inhomogeneous structures under temperature changes.

This paper analyses longitudinal fracture. It should be immediately pointed out that longitudinal fracture in beam-like structures has been extensively studied in many publications [10-16]. However, the aforementioned publications consider longitudinal fracture mainly in simply supported and cantilevered beam structures, although in engineering practice, beams with other boundary conditions are often used. Another characteristic of the aforementioned publications is that they usually deal with beams of linear-elastic behaviour. In view of these findings, the aim of this paper is to analyse longitudinal failure in continuously inhomogeneous nonlinear elastic bars with fixed supports under temperature change. In particular, a bar with circular cross-section is treated. The crack in the bar is a circular cylindrical surface. Since both supports of the bar are fixed, it is a statically indeterminate structure, therefore temperature change induces stresses that affect longitudinal failure. The bar is continuously inhomogeneous along its length. Therefore, the material parameters are smooth functions of the longitudinal coordinate of the bar. The SERR in the bar under temperature change is derived. The SERR verification is performed using an approach published in scientific literature. It is studied how the SERR changes due to variation of the temperature and the distribution of material parameters longitudinally to the bar. The influence of the geometric parameters of the bar configuration also is evaluated by applying the obtained SERR solution to temperature changes. Possible applications of the solution in the structural design of bars with fixed supports are also presented. Finally, a promising direction for further development and sophistication of the present analysis is indicated.

ANALYSIS

The bar studied in this paper is depicted in Fig. 1.

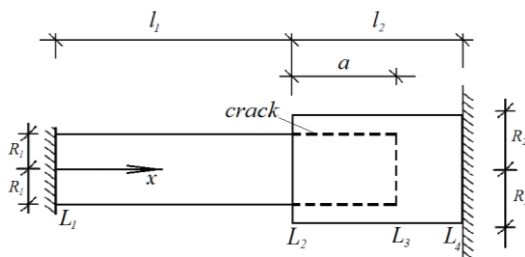


Figure 1. Bar with fixed supports.

The cross-section of the bar is a circle. The bar has two portions, L_1L_2 and L_2L_4 , with different radii, namely R_1 and R_2 . Furthermore, the bar hosts a longitudinal crack of length a , in portion L_2L_3 . The crack represents a circular cylindrical surface of radius R_1 . The front of the crack is in bar section L_3 . The bar is under uniformly distributed temperature change t . Both supports of the bar are fixed, i.e., the bar is a statically indeterminate system.

The mechanical behaviour of the bar is nonlinear elastic and is treated by the constitutive law given in Eq.(1), [17],

$$\sigma = \frac{\varepsilon}{D + Q\varepsilon}, \quad (1)$$

where: σ and ε are stress and strain; D and Q are material parameters. Since the material is continuously inhomogeneous along the bar length, D and Q change smoothly along the axis x , as given in Eqs.(2) and (3),

$$D = D_{L_1} + \frac{D_{L_4} - D_{L_1}}{(l_1 + l_2)^\beta} x^\beta, \quad (2)$$

$$Q = Q_{L_1} + \frac{Q_{L_4} - Q_{L_1}}{(l_1 + l_2)^\delta} x^\delta, \quad (3)$$

where

$$0 \leq x \leq l_1 + l_2. \quad (4)$$

In Eqs.(2) and (3), D_{L_1} and D_{L_4} are values of D in sections L_1 and L_4 of the bar, Q_{L_1} and Q_{L_4} are values of Q in the corresponding sections, and β and δ are parameters. The origin of axis x is in section L_1 , as depicted in Fig. 1.

The coefficient of thermal expansion α_t also changes smoothly along the bar length. Equation (5) describes the change of α_t along axis x ,

$$\alpha_t = \alpha_{tL_1} + \frac{\alpha_{tL_4} - \alpha_{tL_1}}{(l_1 + l_2)^\lambda} x^\lambda, \quad (5)$$

where

$$0 \leq x \leq l_1 + l_2. \quad (6)$$

Here, α_{tL_1} and α_{tL_4} are values of α_t in sections L_1 and L_4 of the bar, λ is a parameter.

Since both supports of the bar are fixed (Fig. 1), the uniformly distributed temperature change induces an axial force. The mutual axial displacement Δl of the bar end sections, L_1 and L_4 is zero, i.e.,

$$\Delta l = 0, \quad (7)$$

where

$$\Delta l = \Delta l_{L_1L_3} + \Delta l_{L_3L_4}. \quad (8)$$

Here, $\Delta l_{L_1L_3}$ and $\Delta l_{L_3L_4}$ are the prolongations of bar portions L_1L_3 and L_3L_4 , in respect. They are obtained by using Eqs. (9) and (10),

$$\Delta l_{L_1L_3} = \Delta l_{L_1L_3t} + \Delta l_{L_1L_3N_{L_1L_3}}, \quad (9)$$

$$\Delta l_{L_3L_4} = \Delta l_{L_3L_4t} + \Delta l_{L_3L_4N_{L_3L_4}}, \quad (10)$$

where: $\Delta l_{L_1L_3t}$ and $\Delta l_{L_3L_4t}$ are the prolongations due to temperature change; $\Delta l_{L_1L_3N_{L_1L_3}}$ and $\Delta l_{L_3L_4N_{L_3L_4}}$ are prolongations induced by axial forces. The prolongations are evaluated as

$$\Delta l_{L_1L_3t} = \int_0^{l_1+a} \alpha_t dx, \quad (11)$$

$$\Delta l_{L_3L_4t} = \int_0^{l_1+l_2} \alpha_t dx, \quad (12)$$

$$\Delta l_{L_1L_3N_{L_1L_3}} = \int_0^{l_1+a} \varepsilon_{L_1L_3} dx, \quad (13)$$

$$\Delta l_{L_3L_4N_{L_3L_4}} = \int_0^{l_1+l_2} \varepsilon_{L_3L_4} dx, \quad (14)$$

where: $\varepsilon_{L_1L_3}$ and $\varepsilon_{L_3L_4}$ are strains in portions L_1L_3 and L_3L_4 of the bar. Then we transform Eqs.(9) and (10) as

$$\Delta l_{L_1L_3} = \int_0^{l_1+a} \alpha_t dx + \int_0^{l_1+a} \varepsilon_{L_1L_3} dx, \quad (15)$$

$$\Delta l_{L_3L_4} = \int_{l_1+a}^{l_1+l_2} \alpha_t dx + \int_{l_1+a}^{l_1+l_2} \varepsilon_{L_3L_4} dx. \quad (16)$$

The strains are expressed as functions of stresses using Eq.(1) as given in Eqs.(17) and (18),

$$\varepsilon_{L_1L_3} = \frac{\sigma_{L_1L_3} D}{1 - \sigma_{L_1L_3} Q}, \quad (17)$$

$$\varepsilon_{L_3L_4} = \frac{\sigma_{L_3L_4} D}{1 - \sigma_{L_3L_4} Q}. \quad (18)$$

By using Eqs.(8), (15)-(18), we transform Eq.(7) to:

$$\int_0^{l_1+a} \alpha_t dx + \int_0^{l_1+a} \frac{\sigma_{L_1L_3} D}{1 - \sigma_{L_1L_3} Q} dx + \int_{l_1+a}^{l_1+l_2} \alpha_t dx + \int_{l_1+a}^{l_1+l_2} \frac{\sigma_{L_3L_4} D}{1 - \sigma_{L_3L_4} Q} dx = 0. \quad (19)$$

Since the bar is in equilibrium, the axial forces $N_{L_1L_3}$ and $N_{L_3L_4}$ in portions L_1L_3 and L_3L_4 of the bar are equal,

$$N_{L_1L_3} = N_{L_3L_4}. \quad (20)$$

The axial forces are presented as functions of stresses by Eqs.(21) and (22),

$$N_{L_1L_3} = \iint_{(A_{L_1L_3})} \sigma_{L_1L_3} dA, \quad (21)$$

$$N_{L_3L_4} = \iint_{(A_{L_3L_4})} \sigma_{L_3L_4} dA. \quad (22)$$

Then, Eq.(19) is transformed as

$$\iint_{(A_{L_1L_3})} \sigma_{L_1L_3} dA = \iint_{(A_{L_3L_4})} \sigma_{L_3L_4} dA. \quad (23)$$

From the fact that the stresses induced by axial forces are distributed uniformly in bar cross-sections, it follows that Eq.(23) can be re-written as

$$\sigma_{L_1L_3} A_{L_1L_3} = \sigma_{L_3L_4} A_{L_3L_4}, \quad (24)$$

where the cross-section areas $A_{L_1L_3}$ and $A_{L_3L_4}$ are

$$A_{L_1L_3} = \pi R_1^2, \quad (25)$$

$$A_{L_3L_4} = \pi R_2^2. \quad (26)$$

Equations (19) and (24) are used for determining the stresses by MATLAB®.

The SERR G in the nonlinear elastic bar is obtained by applying Eq.(27),

$$G = \frac{dU^*}{dA_{dc}}, \quad (27)$$

where: U^* is complementary strain energy in the bar structure; dA_{dc} is infinitesimal growth in the area of the delamination crack. The quantity, dA_{dc} is

$$dA_{dc} = 2\pi R_1 da, \quad (28)$$

where: da is infinitesimal growth in the length of the delamination crack. Thus, we replace Eq.(27) by

$$G = \frac{dU^*}{2\pi R_1 da}. \quad (29)$$

The complementary strain energy is determined as

$$U^* = U_{L_1L_3}^* + U_{L_3L_4}^*. \quad (30)$$

Complementary strain energy in portion L_1L_3 is evaluated as

$$U_{L_1L_3}^* = A_{L_1L_3} \int_0^{l_1+a} u_{0L_1L_3}^* dx, \quad (31)$$

where the density of complementary strain energy $u_{0L_1L_3}^*$ is defined by equation

$$u_{0L_1L_3}^* = \sigma_{L_1L_3} \varepsilon_{L_1L_3} - \int_0^{\varepsilon_{L_1L_3}} \sigma_{L_1L_3} d\varepsilon_{L_1L_3}. \quad (32)$$

Analogically, for the complementary strain energy in portion L_3L_4 of the bar, we have

$$U_{L_3L_4}^* = A_{L_3L_4} \int_{l_1+a}^{l_1+l_2} u_{0L_3L_4}^* dx, \quad (33)$$

where $u_{0L_3L_4}^* = \sigma_{L_3L_4} \varepsilon_{L_3L_4} - \int_0^{\varepsilon_{L_3L_4}} \sigma_{L_3L_4} d\varepsilon_{L_3L_4}. \quad (34)$

SERR is extracted from Eq.(29) by MATLAB®. An approach from the literature is used for checking of the SERR solution obtained here, [18]. The application of this approach for the longitudinal crack problem under consideration gives

$$G = \frac{1}{R_1} \left(\int_0^{R_1} u_{0bh}^* R dR - \int_0^{R_2} u_{0ah}^* R dR \right). \quad (35)$$

The complementary strain energy densities u_{0bh}^* and u_{0ah}^* refer to cross-sections behind and ahead of the crack front. The use of Eq.(35) results in SERR (via MATLAB) which is a match of the SERR extracted from Eq.(29).

INFLUENCE OF TEMPERATURE CHANGE AND OTHER PARAMETERS ON THE SERR

The analysis is developed at $l_1 = 0.300$ m, $l_2 = 0.600$ m, $R_1 = 0.003$ m, $R_2 = 0.012$ m, $a = 0.400$ mm, $t = 60$ °C, $\beta = 0.5$, $\delta = 0.6$ and $\lambda = 0.7$. It is also demonstrated how the analysis can be applied in the design of structures subjected to temperature change (for instance, to determine the radius of the bar cross-section). Figures 2-4 illustrate the influence of various parameters on the SERR established by analysis (SERR is shown in dimensionless form). Determination of the radius is illustrated in Fig. 5. The problem for determining the critical temperature is treated too (Fig. 6).

First, the influence of the coefficient of thermal expansion along bar length on SERR is analysed, as well as the influence of parameter D_{L1} . These influences are illustrated in Fig. 2, where the relation between SERR and $\alpha_{tL4}/\alpha_{tL1}$ ratio is plotted at three D_{L4}/D_{L1} ratios. In Fig. 2 we observe a growth of SERR with a rise in $\alpha_{tL4}/\alpha_{tL1}$. Growth in SERR with increasing ratio D_{L4}/D_{L1} is also observed (Fig. 2).

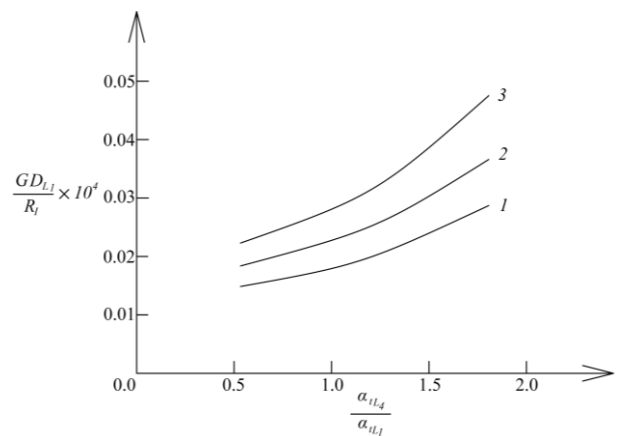


Figure 2. SERR vs. ratio $\alpha_{tL4}/\alpha_{tL1}$ at $D_{L4}/D_{L1} = 0.5$ (curve 1), $D_{L4}/D_{L1} = 1.0$ (curve 2), and $D_{L4}/D_{L1} = 2.0$ (curve 3).

The following is an analysis of the influence of temperature change in the bar on SERR in relation to ratio a/l_2 . In this regard, SERR is plotted against temperature in Fig. 3 at three a/l_2 ratios. A significant increase in SERR resulting from temperature rise can be seen in Fig. 3. An increase in SERR as a result of increasing a/l_2 ratio can also be seen (Fig. 3).

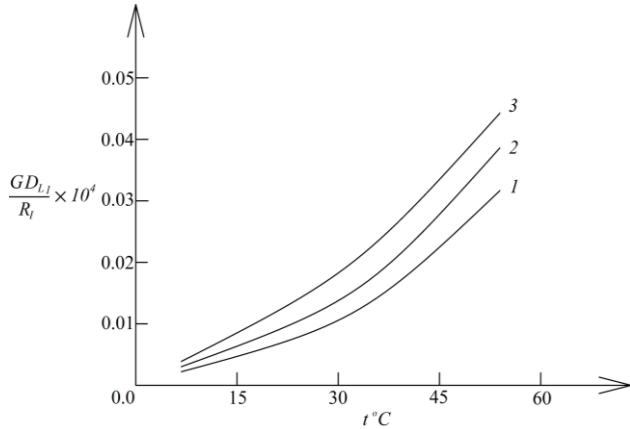


Figure 3. SERR vs. temperature at $a/l_2 = 0.2$ (curve 1), $a/l_2 = 0.4$ (curve 2), and $a/l_2 = 0.6$ (curve 3).

Next, influences of bar geometry and change of parameter Q in the bar longitudinal direction on SERR are analysed via l_2/l_1 and Q_{L4}/Q_{L1} ratios, respectively. Figure 4 shows the variation of SERR with increasing l_2/l_1 ratio at three Q_{L4}/Q_{L1} ratios. We observe that SERR rises smoothly with the rise of l_2/l_1 ratio (Fig. 4).

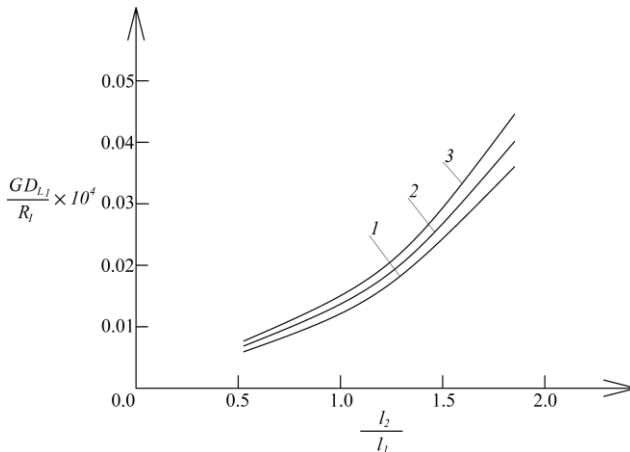


Figure 4. SERR vs. ratio l_2/l_1 at $Q_{L4}/Q_{L1} = 0.5$ (curve 1), $Q_{L4}/Q_{L1} = 1.0$ (curve 2), and $Q_{L4}/Q_{L1} = 2.0$ (curve 3).

It is also demonstrated how to determine the radius of the cross-section of the bar in portion L_2/L_4 based on fracture mechanics by using the solution of SERR. In this regard, the variation of SERR with rise of R_2/R_1 ratio is depicted in Fig. 5. The ratio at which SERR reaches the fracture toughness of the material G_c :

$$G = G_c, \quad (36)$$

is used to determine the desired radius, as shown in Fig. 5.

Finally, it is shown that the problem for determining the critical temperature in the bar with a longitudinal crack can also be treated with the help of the solution of SERR, derived in section 2 of the paper. Here, the critical temperature

t_c is understood as the temperature at which crack growth begins. Therefore, when the temperature reaches its critical value t_c , the SERR in the bar reaches the fracture toughness G_c . Namely this condition is applied to determine the critical temperature. The way for determining the critical temperature is presented in Fig. 6.

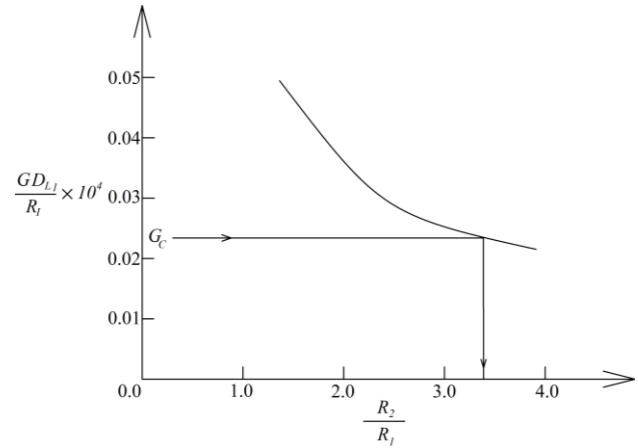


Figure 5. SERR vs. ratio R_2/R_1 .

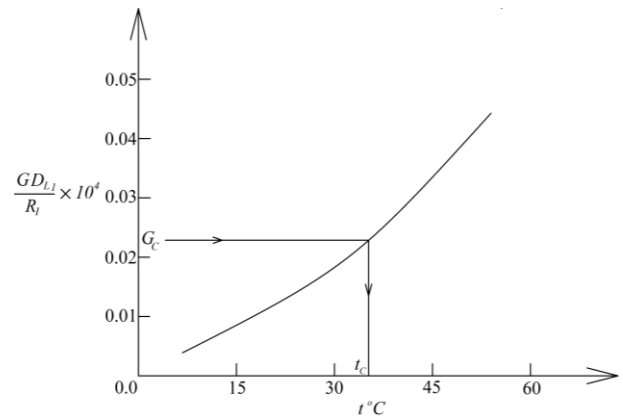


Figure 6. Determination of the critical temperature.

CONCLUSIONS

The analysis developed in this paper helps to understand the longitudinal fracture behaviour of continuously inhomogeneous bars with fixed supports in cases when the bars are subjected to temperature changes. The mechanical behaviour of bars is nonlinear elastic. All material parameters represent smooth functions of the longitudinal coordinate in the bar structure. The solution of SERR obtained here can be used to examine how the longitudinal fracture performance of bars evolves when various parameters of continuously inhomogeneous bars are changed. It is found that the SERR is significantly affected both by changes in purely geometric parameters such as the ratio of lengths of the two portions of the bar, and by the distribution of material parameters of the nonlinear stress-strain law along the length of the bar. The effect of growth of l_2/l_1 , D_{L4}/D_{L1} and Q_{L4}/Q_{L1} ratios is an increase in SERR.

Changes in SERR caused by changing the ratios α_{L4}/α_{L1} and a/l_2 , as well as temperature are examined also. An increase in SERR is detected when ratios α_{L4}/α_{L1} and a/l_2 , and temperature increase. The derived solution of SERR has

useful applications in the design of bars with fixed supports. It is considered how the solution can be used to determine the radius of the bar. A method for determining the critical temperature in bars with a longitudinal crack based on the obtained solution is also presented. The study of the case of a continuously inhomogeneous bar with fixed supports, subjected to both mechanical loading and temperature change, can be indicated as an important direction for further development and improvement of the present longitudinal fracture analysis.

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