Effects of Tangential Strains and Shielding in Large Scale Yielding in Multi-Layered Architectures for Bearings

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Abstract. Multi-layered bearing systems used in the automotive industry show shielding and anti-shielding effects that reduce or amplify the crack driving force under large scale yielding conditions. Using finite element analysis, it is shown that shielding in such systems results in path deflection and bifurcation despite the absence of mixed-mode loading. As the crack approaches a stiff layer, the tangential strains measured around a blunted crack tip model show a maximum corresponding to the direction of crack propagation. The asymmetric distribution of such strains indicates the effect of shielding and the likelihood of the tip to deflect or bifurcate. The suitability of bi-layer and tri-layer bearing architectures is assessed through crack path and respective crack driving force predictions.

Introduction

Fatigue and fracture failure are issues of extreme industrial relevance due to the cost involved in spare parts, service and lead times. New materials and design processes have supported the introduction of more demanding service conditions. This trend is present in the automotive industry where power efficiency and component packaging drive the requirement for smaller, more lightweight and durable components. The design of plain bearings is one case in point, due to its importance in the powertrain system and its strategic position within the engine. In machine design, more emphasis is usually given to heavier components such as connecting rods, pistons or shafts [1]. However, the bearing design process is complex and involves assessment of manufacture, assembly and service conditions. The analysis of the latter is especially interesting and challenging since it is based on the hydrodynamic film pressure, as shown in Fig. 1, and the resulting housing deformation. The hydrodynamic film pressure shows very steep gradients over the bearing surface causing mixed-mode loading and, consequently, complex crack growth patterns.

In practice, pure fatigue damage in bearings is rare; usually a combined set of mechanisms, such as cavitation erosion, wear, inter-layer cracking and corrosion, reduce the bearing performance [2]. A typical damage observed in plain bearings is lining detachment, releasing fine fragments into the hydrodynamic film and eroding the journal or bearing surface. The erosion of the surface modifies the hydrodynamic film profile causing even larger pressure gradients and thus greater tendency to fatigue failure. The lining detachment is caused by a surface crack growth in the radial and axial direction of the bearing. As this crack grows, it tends to deflect or bifurcate increasing the likelihood of coalescence with another crack and, in this way, release of a fragment of lining as shown in Fig. 1.

A good example of development in materials and architectures is the application of a number of layers with different mechanical properties to enhance bearing performance. These multi-layered systems provide the required compromise between stiffness and strength through a stiff backing layer, and shock absorption and conformability through the lining. An additional attribute of multi-layered structures is the shielding effect that reduces the growth rate as cracks approach stiffer layers [3], increasing the service life. Conversely, the opposite effect is observed as the crack approaches a more compliant layer.

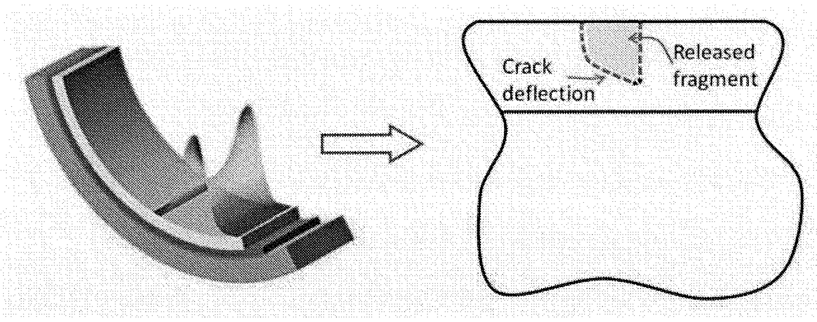

Figure 1. Multi-layered plain bearing and fragment release caused by hydrodynamic film pressure.

In addition, this shielding has also been shown to cause crack deflection and bifurcation despite the absence of far-field mixed-mode loading under cyclic three-point bending conditions [4], as shown in Figure 2. Numerical analysis [4] based on J integral estimations reported highly deflected bifurcated crack paths, corresponding to maximum crack driving force (CDF) values, as the crack tip approaches a stiffer layer. This was explained in terms of the crack following the path that offers the least resistance or maximizes the CDF in accordance with experimental results.

Crack path deflection has been extensively studied in brittle and ductile materials [5-7]; crack growth under mode I-dominant, monotonic loading can be consistently simulated based on different deflection criteria. Most applications to engineering problems have used closed-form solutions for the maximum tangential stress [8] obtained in the context of LEFM. A single approach has not however been tested for optimum performance over a full range of mixed-mode loading.

The objective of this work is to investigate the path and CDF evolution for growing cracks in multi-layer systems with mechanical properties mismatch that are subjected to large-scale yielding (LSY). Thus, it will be possible to assess the impact of such architectures on crack growth under loading causing extensive plasticity, as found in plain bearings. A comparative study between bi-layer and tri-layer architectures is carried out here to assess the influence of a compliant interlayer, which is found in some plain bearing designs as it provides a protective deposition layer for the steel and improves the bonding between layers. The state of stress around the crack tip is also studied to assess the conditions that promote crack deflection and bifurcation despite the absence of far-field mixed-mode loading.

Methodology

This study is based on two-dimensional FE analyses and appropriate fracture mechanics concepts applicable to stationary and propagating cracks. Quasi-static simulations of crack growth are performed by estimating the state of stress and strain around the crack tip and the adopted CDF parameter for straight and deflected crack paths.

The study is divided into two stages. Firstly, straight cracks of different lengths are modelled in a bi-layer architecture, to study a pure shielding case, and a tri-layer architecture, to study the combined effect of anti-shielding and shielding. At this stage, a pure mode I loading is applied to replicate the experimental conditions that led to bifurcated and deflected paths and, in this way, to study the crack tip stresses and strains through refined FE meshes. Secondly, deflected and bifurcated paths are simulated to investigate their effects on the CDF estimates and their tendency to grow parallel to the layers' orientation. At the same time, the influence of the multi-layered architecture is assessed by studying the CDF evolution as the crack tip and bifurcation point approach the layers interface. The models used at both stages are shown in Fig. 3.

The performed FE analyses are based on the general-purpose software ANSYS, version 11.0. Two-dimensional models were built using re-meshing schemes around straight or deflected propagating cracks. Elasto-plastic material models were used according to the data presented in Fig. 2 [9]. The compliance matrix was re-calculated after each convergence iteration in the solution process to account for the effect of the large deformations observed in the tests. Parametric quarter-point elements [10] in spider-web configurations were found to be excessively distorted in preliminary simulations of three-point bending tests under high loads causing high plastic strains, especially in the compliant interlayer. For this reason, a blunted tip [11] modelled as a semi-circle of very small radius was adopted to reliably predict large crack tip deformations. Relevant stress, strain and displacement values were read relative to a local polar frame of reference with origin at the centre of the semi-circle.

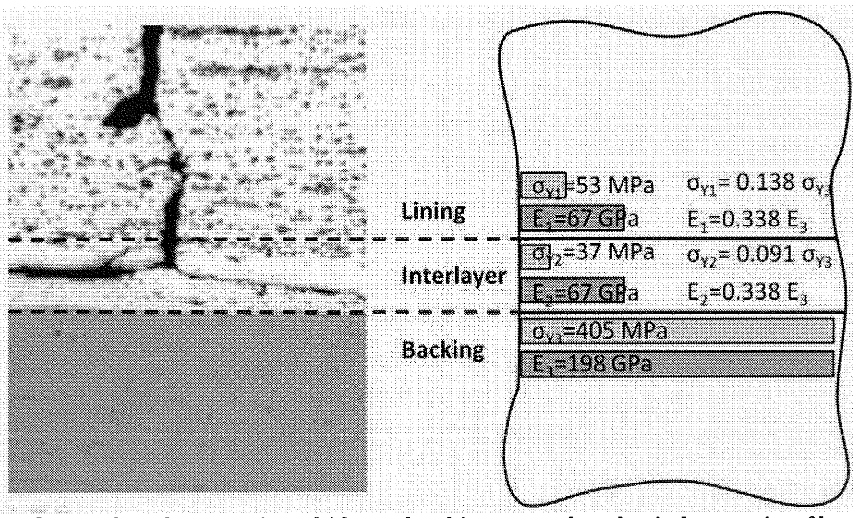

Figure 2. Observed crack pattern in multi-layered architecture and mechanical properties of layers.

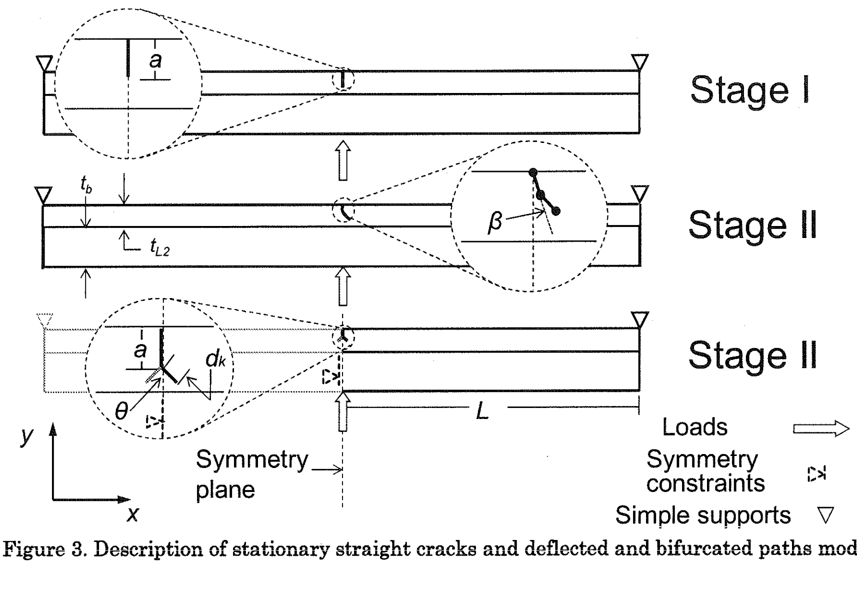

Figure 3. Description of stationary straight cracks and deflected and bifurcated paths models.

The crack tip opening displacement (CTOD) was estimated in the FE models as representative of the CDF, being easier to compute in comparison to the J integral for cracks propagating in multi-layered systems under LSY conditions. The CTOD is also theoretically better suited for characterising cyclic loading in the context of a fatigue crack propagation law. Another advantage of CTOD is its direct computation from FE displacement results. The CTOD was measured as the relative displacement of two nodes placed at the two ends of the blunted tip semi-circle.

The direction of crack deflection was evaluated through the maximum tangential strain (MTSN) criterion [5], considered a more suitable criterion than stress-based approaches for large plastic strain analyses. Its implementation was carried out from FE estimates at the nodes placed at 5° intervals around the blunted tip. To obtain a point-wise estimate a second order interpolation was implemented using the crack tip tangential strains (CTTS) at three adjacent nodes.

Stage I: Stationary straight cracks

The study of straight cracks is the starting point to evaluate the magnitude of shielding and anti-shielding mechanisms in the studied architectures. The introduction of the interlayer does not play a significant role in the overall stiffness of the component in bending with a layer thickness that corresponds to 1.8 % of the overall thickness and 9.5 % of the lining. However, its impact on the CDF is significant as shown in Fig. 4.

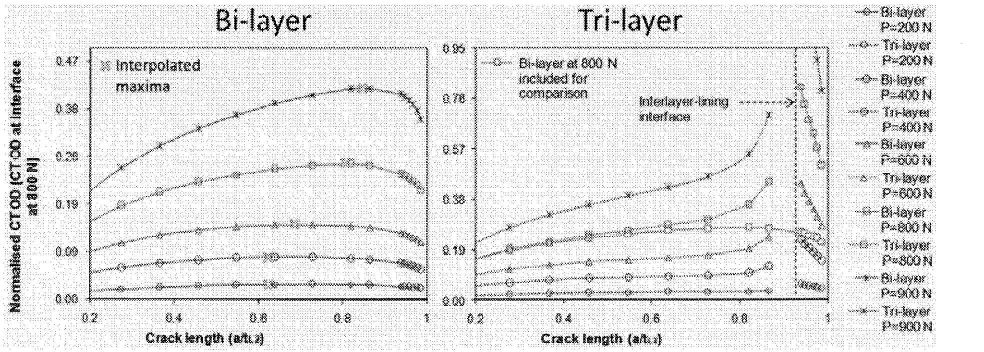

Figure 4. Observed crack pattern in multi-layered architecture and mechanical properties of layers.

In this as well as all subsequent graphs, the CTOD results are plotted against the ratio of the crack length a to the lining thickness t_{L2} of the bi-layer system (see Fig. 3). The shielding and amplification trends observed are consistent with those reported in similar previous investigations based on J-integral estimates of systems with principally plastic [12] but also elastic [4] mismatch. In the bi-layer architecture, the shielding effect is indicated by the decrease in CTOD as the crack approaches the stiffer steel layer. In the tri-layer architecture, the amplification effect is noted when the crack approaches the more compliant interlayer, and shielding when the crack approaches the stiffer backing within the interlayer. The application of higher loads and subsequent spread of plasticity led to greater mismatches between layers, which caused increased CTOD gradients and therefore more pronounced shielding and amplification at lower crack lengths; in contrast, the spread of plasticity into the backing layer of the bi-layer strip at the highest load reduced the mismatch between the layers and, as a consequence, shifted the CTOD maximum closer to the lining/backing interface.

The CTOD as CDF parameter appears to be well suited for investigating crack shielding and amplification in multi-layered systems under LSY conditions comparable to the ones observed in the bearing operation. The results obtained with CTOD are consistent with those previously published [3, 12-14], which mostly used the J integral as CDF parameter.

The evaluated crack tip tangential strains (CTTS) showed different patterns depending on the applied load, crack length, layer in which the crack tip is located and architecture analyzed. At crack lengths below $0.45t_{L2}$ the CTTS curves had a very similar curvature corresponding to a clearly identified maximum value when plotted against the angular position around the blunted tip; this maximum indicated the normal to the interface as the preferred direction of propagation in accordance to experimental observations. For $a/t_{L2} > 0.45$, the CTTS profiles showed different trends in the two architectures when plotted versus the crack length; this can be seen in Fig. 5. The tri-layer architecture yields a clear maximum for increasing crack length in comparison to the bi-layer architecture for which the maximum appears to spread over a range of possible deflection angles at the same load level.

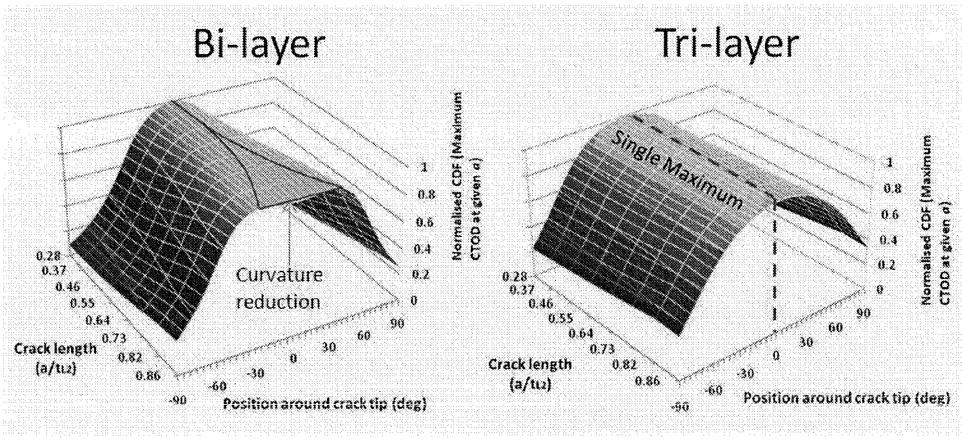

Figure 5. CTTS evolution in bi-layer and tri-layer architectures under P=200 N.

At low loads, the CTTS curves for the tri-layer showed a clear maximum point at every tested crack length. As the load was increased, a less significant curvature reduction was observed, in comparison to the bi-layer case, and the appearance of such a reduction was observed closer to the layers' interface. The CTTS variation indicates the natural likelihood of either architecture to contain bifurcated or deflected cracks. This analysis is consistent with experimental observations in bearings where bi-layer architectures have shown more consistently deflected or bifurcated paths in the lining, while tri-layer architectures usually show similar paths within the interlayer and to a lesser extent in the lining. It is noteworthy that no inference from these findings on the life of the bearing has been made up to this point.

Stage II: Deflected and bifurcated paths

Deflections and bifurcations have been widely studied in crack propagation problems due to their importance in determining the crack path and CDF. Detailed observation of tested components has shown coalesced cracks that release lining fragments under bearing service conditions; similar behaviour has been observed in flat strip specimens of the same architecture under simpler three-point bending tests. However, it is difficult to confirm whether a deflected single tip or bifurcated crack is responsible for such phenomena.

Deflected paths. The study of straight cracks showed the likelihood of the crack to deflect and the shielding and anti-shielding effects caused by both architectures. The CTTS indicate that as the crack approaches a stiff layer the maximum value spreads over a range of angles so that any asymmetric feature, such as the material micro-structure for instance, can cause a deflection from the straight path. In order to study such a scenario, an automatic crack extension routine based on the CTTS estimates was implemented within ANSYS APDL (ANSYS Parametric Design Language) recording the CDF estimates as the numerical process was carried out. This routine extended the crack by small straight segments. The crack tip was allowed to change its direction from segment to segment, indicated by the angle β in Fig. 3, according to the search of the numerical maximum of the estimated CTTS curves.

The crack growth simulation in the bi-layer lining revealed the tendency for the crack to deflect, as predicted in the analysis of straight cracks. The observed deflections were dependent on the extent of plasticity caused by the applied load. Under low loads, insignificant deflections were forecasted by the CTTS curves; deflections around 20° were only observed under P=800 N and very close to the layers interface.

The prediction of small deflections led to the consideration of deflections possibly arising from the irregular multi-phase micro-structure observed in tested bearings that would modify the solution based on problem symmetry. This scenario was tested in both architectures at P=200 N and P=800 N by introducing a large artificial deflection at some crack length. The corresponding results showed that the crack has a prefered path according to the adopted deflection criterion and that any induced deflections only alter locally the path and CDF estimates; a swift return to the preferred conditions occurs.

The analysis for the tri-layer lining resulted in straight paths and CDF estimates identical to the ones obtained for straight cracks; the small deviations estimated during crack propagation can be attributed to numerical error. The crack growth simulation in the interlayer showed a deflected path that approached in an asymptotical manner the interlayer-backing interface, as shown in Fig. 6, under any applied load according to experimental data [9]. The introduction of an artificially induced deflection in this architecture replicated the trend observed in the bi-layer architecture.

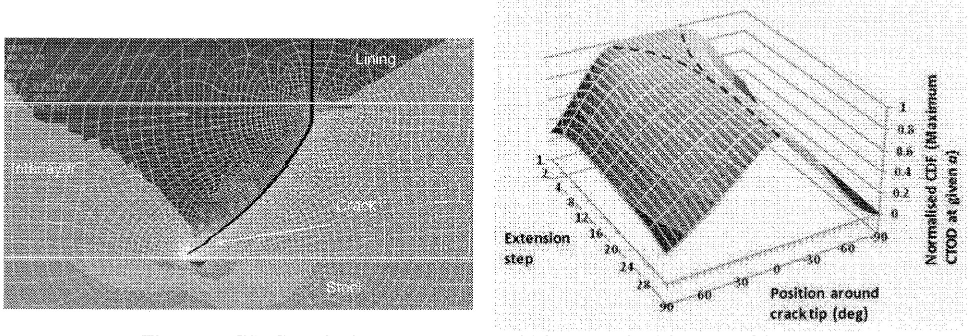

Figure 6. CTTS evolution at P=200 n in bi-layer and tri-layer architecture.

The tri-layer scenario only showed an extension of crack path length with the tendency to propagate along the interlayer and avoiding penetrating the stiff backing. It is noteworthy that this path will extend until another crack coalesces with it and, subsequently, cause a fragment of the lining to detach. Within the interlayer, the crack tip was completely within the plastic zone that extended over most of the containing layer increasing the mismatch between layers and the constraint on the crack tip leading to favourable conditions to overcome the influence of problem symmetry.

Bifurcated paths. Path bifurcation has a considerable effect on the CDF estimates; this strongly depends on the bifurcation angle θ, shown in Fig. 3. The effect of this angle was examined along with that of the crack length a before bifurcation. Small crack kink lengths d_k (see Fig. 3) were used to study the crack growth conditions as close as possible to the bifurcation point (0.02 t_{L2} for the bilayer case and 0.005 t_{L2} for the tri-layer). The CDF values obtained from this analysis, shown in Fig. 7, confirm the importance of the proximity to a stiff layer as shown for straight cracks in both architectures. At the same time, for any given crack length a, a bifurcation angle θ corresponding to a maximum CFD can be identified. As the crack length a was extended, the angle corresponding to maximum CDF shifted to greater values (greater separation between bifurcation kinks). The shift of the optimum angle was more pronounced in the tri-layer architecture where values up to 55° where found, in contrast to 45° in the bi-layer architecture. Greater d_k values also resulted in a less significant shift of the optimum angle than the one observed for a (within a range of 0.02 t_{L2} and 0.05 t_{L2} in the bi-layer architecture).

Previous elastic analysis on bifurcated arrangements in single material specimens reported reductions of the CDF around 30% and 50% for bifurcated angles θ between 30° and 50° estimating that an optimum angle between cracks could be around 16°. The analysed bifurcated arrangements, considering the elasto-plastic properties of the material, in bi-layer and tri-layer architectures showed greater optimum kink angles that were influenced by the proximity to the interface and CDF reductions of around 70%.

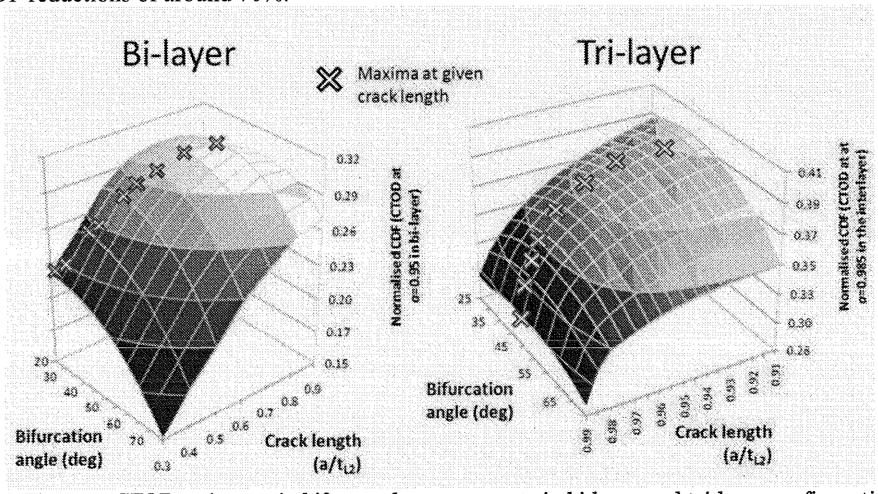

Figure 7. CTOD estimates in bifurcated arrangements in bi-layer and tri-layer configurations.

Disscussion

The study of crack propagation in multi-layered systems under three-point bending helps the identification of circumstances leading to path deflection and bifurcation and the associated consequences. In a scenario where crack bifurcation and deflection is not present, it is clear that a bi-layer architecture and the associated shielding effect would retard crack growth to great extent. However, it has been shown experimentally and numerically [4, 9] that as the crack approaches the layers interface, the tendency to bifurcate grows despite the absence of mixed-mode loading; such conditions would contribute to the crack tip deflection after bifurcation.

In the context of bearing design, it should be noted that mixed-mode loading is present in such components promoting crack deflection and bifurcation. Single-crack deflection in bearings occurs according to the mixed-mode loading conditions; such deflections have been frequently observed in bi-layer bearing systems in the lining [15]. On the other hand, straight crack growth in the tri-layer architecture is promoted as it approaches the interlayer, allowing the crack to propagate deeper into the lining and interlayer, where excessive path deflection due to bifurcation would finally lead to the detachment of the lining in a longer service life.

Bifurcated crack patterns have been shown to be beneficial in terms of the calculated CDF and the tendency for deflection as the crack tip approaches the lining-backing interface. Nevertheless, these attributes mainly occur in the context of a single flaw. A bifurcated crack in a bi-layer architecture could deflect or bifurcate for as short crack length as $0.5t_{L2}$, while the straight crack is attracted to the interlayer in the tri-layer architecture. The coalescence of cracks and lining particle release are clearly dependent on the random distribution of flaws around the material; nevertheless, the introduction of a soft interlayer promotes the crack growth into the interlayer crossing the entire lining and reducing the probabilities of an early lining release. Field tests in both architectures have also indicated an extended life for this tri-layer architecture along with a less significant variability.

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