Failure Analysis of Bolted Composite Joint- A Review

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***Abstract*— A review of publications associated with the failure of bolted composite joints in this paper has been carried out. The study covered the work done from 2005 to 2012. Mechanical fasteners often cause a reduction of load capacity of the composite structure because of the complicated stress field near the hole area. Consequently, special attention must be given to design of fasteners. The design of efficient structural attachments represents one of the major challenges in the development of composite structures. Because of its generic nature, the joint design deserves a separate treatment as a case study. Characterization of joint failure in bolted composite laminates is complicated because of the large number of parameters involved. A large part of the research, done on mechanically fastened joints so far, has been concerned with the experimental determination of the influence of geometric factors on the joint strength. In this paper, the advances that took place in analytical approaches, experimental tests and finite element analysis associated with composite bolt designing have been studied. A review of publications associated with the failure of bolted composite joints in this paper has been carried out. The study covered the work done from 2005 to 2012. Mechanical fasteners often cause a reduction of load capacity of the composite structure because of the complicated stress field near the hole area. Consequently, special attention must be given to design of fasteners. The design of efficient structural attachments represents one of the major challenges in the development of composite structures. Because of its generic nature, the joint design deserves a separate treatment as a case study. Characterization of joint failure in bolted composite laminates is complicated because of the large number of parameters involved. A large part of the research , done on mechanically fastened joints so far, has been concerned with the experimental determination of the influence of geometric factors on the joint strength. In this paper, the advances that took place in analytical approaches, experimental tests and finite element analysis associated with composite bolt designing have been studied.**

***Keywords*— Bolted joint, composite, failure modes, finite element method, geometric factors, load capacity, stress field.**

I. INTRODUCTION

Composite materials are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct within the finished structure. We can engineer them specifically to meet our needs on a case to case basis. Composite materials owe their growing usage in different branches of engineering to their advantages over conventional metal materials. They have high strength to weight and stiffness to weight ratios. This has led to the development of lighter structures .The applications require joining of composites either to composite or to metals. Bolt joints are unavoidable in complex structures because of their low cost, simplicity and facilitation of disassembly for repair. Bolted joints require holes in the composite structure. These holes cause large stress concentrations, decrease the load holding capacity and increase the complexity of the numerical analysis. It can be said that the joint properties have a significant effect on failure as well as composite properties. The design goal of a bolted composite lap joint is to ensure load transfer without failure of the joint. The composite joints have become a very important aspect because the structural properties of the composite structure are determined by its joints. 70% of composite structure damage occurs in joint. Because of this, so many researchers are interested in bolted composite joints.

It is important, therefore, to determine the failure strength and failure modes of these joints. A major goal of composite bolted joint research has been to determine the effect of various bolting parameters on the joint strength. The bolting parameters that have been studied include geometric factors, material properties, coefficient of friction, bolt shape, clearance and torque. These studies have provided strategies to design composite bolted joints avoiding catastrophic failure. The basic failure modes in bolted fiber reinforced materials are cleavage, bearing, net- tension and shear-out failures as has been shown in fig.1. From these failure modes only bearing damage produces a progressive failure, thus composite bolted joints are designed to fail under this mode. Bearing failure occurs in the material immediately adjacent to the contacting bolt surface due to primarily compressive stresses and leading to a non-linear behavior of composite plates.

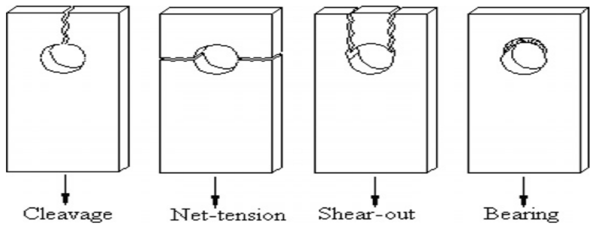

Fig.1. Failure modes in bolted fiber reinforced material.

The assessment of the stresses around the fastener holes becomes critical for damage-tolerant design. Because of the presence of unknown contact stresses and contact region between the fastener and the laminate, the analysis of bolted hole becomes considerably more complex than a traction- free hole. The accurate prediction of the stress distribution along the hole edge is essential for reliable strength evaluation and failure prediction. The knowledge of the failure strength would help in selecting the appropriate joint size in a given application. Bolted joints are three-dimensional in nature. Although the finite element method (FEM) is capable of addressing such joint configurations, it requires considerable computer resources, especially in the presence of multiple bolts. Therefore, identification of critical design parameters and optimization of the joint strength have become a computational challenge with the finite element method.

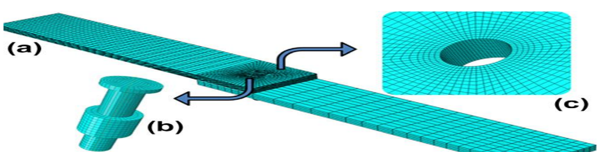

Fig. 2. FE model mesh. (a) complete model. (b) bolt and nut, (c) mesh detail.

Current joint design practices involve analytical approaches , experimental tests and three-dimensional finite element (3-D FE) analysis. In detailed 3-D FE models, each part of the joint is modelled separately as shown in fig.2, while contact models with tight contact tolerances are used to model the interaction between each part. Such models capture effects such as clearance, bolt-torque and detailed contact stresses, friction effects between discrete regions in the joint , the load distribution in multi-bolt joints and material damage propagation .While such models provide accurate solutions for small joint specimens, they suffer from excessive computation time, especially where friction and damage models are present.

II. LITERATURE REVIEW

2005- Kradinov et al.[1] applied genetic algorithm(GA), powerful optimization technique for multiple extrema functions in multidimensional search spaces, in conjunction with stress analysis to achieve optimum designs of bolted composite lap joints. An analysis tool for optimal bolted lap joint designs was developed by combining the complex potential theory and variational formulation in conjunction with the genetic algorithm. Though not a limitation of the method, the capability of this tool has been demonstrated by considering two single-laps bolted joint configurations with eight and thirteen design variables. The objective of the optimization is to ensure the highest strength of the joint. In this study, the laminate thickness, laminate lay-up, bolt location, bolt flexibility, and bolt size are considered as design variables. The contact stresses (bolt loads) are determined by a combined complex potential and variational formulation. In this formulation, the equilibrium equations are satisfied exactly and the boundary conditions are enforced by minimizing the total potential. Xiao et al.[2] performed the experimental investigation, modelling and simulation of bearing strength and failure behaviour of bolted composite joints. McCarthy et al.[3] had experimental study of bolt hole clearance effects in single-lap, multi-bolt composite joint. Lawlor et al.[4] carried out same in double-lap, multi-bolt composite joint.

McCarthy et al.[5,6,7,8,9] used experiments and three dimensional finite element models to study effects of bolt hole clearances and friction in single-bolt, single-lap composite(graphite/epoxy) joints, progressive damage analysis was also performed for multi-bolt composite joint with variable bolt-hole clearance. Riccio et al.[10,11] studied the effects of geometrical and material features on damage onset and propagation in single-lap bolted composite joints under tensile load both experimentally and numerically. Ekh et al.[12] studied the effect of secondary bending on strength prediction of composite, single shear lap joints. The effect of tightening torque and the through-the thickness stress distribution are affected by the secondary bending phenomenon. The eccentric load path in single shear lap joints adds the issue of lateral deflection (or secondary bending) of the joint, which generates a non-uniform contact pressure between the fasteners and the hole edge. A stress singularity is also introduced when the bolt is tilted in its hole as the surface contact changes into a line contact.

2006- Camanho, Lambert et al.[13] presented a new methodology to predict the onset of damage, final failure and failure mode of mechanically fastened joints in composite laminates. The stress distribution at each ply is obtained using semi-analytical or numerical methods. The elastic limit of the joint is predicted using the ply strengths and stress distribution in failure criteria. Final failure and failure mode are predicted using point or average stress models. The methodology proposed is applicable in double-shear joints using quasi-isotropic laminates. A new procedure for dimensioning double-shear mechanically fastened joints in advanced composite materials is proposed. The method is applicable to double-shear bolted or pinned joints under uniaxial or multiaxial loading. New standardized procedures to measure the characteristic distances in tension and in compression used in the model are proposed. The statistical analysis of the experimental results showed that the characteristic distances in tension are a function of both the hole diameter and specimen width. Design charts to calculate the characteristic distances in tension are proposed. Camanho et al.[14] worked on the prediction of in-situ strengths and matrix cracking in composites under transverse tension and in-plane shear. Kelly et al.[15] studied the quasi-static strength and fatigue life of hybrid (bonded/bolted).

Himmel et al.[16] worked on the cyclic fatigue behaviour of carbon fibre reinforced vinyl ester resin composites manufactured by RTM and VARI. Since VARI process cures in room temperature and enable the manufacture of large structures with high mechanical properties under vacuum. So vacuum assisted resin injection process (VARI) can be widely used in the large components, especially in the ship building. For example Visby class corvette was made by VARI process, as the first complete composite corvette, Visby had excellent stealth performance. McCarthy et al.[17] presented a simplified method for determining the effects of bolt–hole clearance on the load distribution in composite multi-bolt joints is presented. The method is applicable to joints with a single column of bolts. It can be applied to both single-lap and double-lap joints. The method is validated against three-dimensional finite element models, and some examples of different clearance cases are shown. It is shown that even small amounts of clearance can significantly alter the load distribution in the joint. Finally the method is used in a parameter study to examine the effects of various joint parameters on load distribution.

2007- Sen et al.[18] performed a failure investigation to determine the failure mode and bearing strength of mechanically fastened bolted-joints in glass fiber reinforced epoxy laminated composite plates, experimentally. Two different geometrical parameters those are the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) were considered. In addition, the preload moments were applied. The experiments were also performed under a clearance. Results showed that failure modes and bearing strengths were considerably affected by the increasing of preloads. Furthermore, when the material and geometrical parameters of composite bolted-joints were changed, the failure behaviour and the values of bearing strengths were fully influenced from this change. Sayman et al. [19] carried out a failure analysis to determine bearing strength of mechanically fastened joints with single bolt in glass–epoxy laminated composite plates under preload, experimentally. The experimental results showed that the magnitudes of bearing strengths in bolted joints were strictly influenced from increasing value of applied preload moments, with changing W/D and E/D ratios, and also ply orientations of laminated composite plates. Pakdil et al.[20] determined the influence of preload moments on failure response of glass–epoxy laminated composite single bolted joints with bolt/hole clearance. To observe the effects of bolted-joint geometry and stacking sequence of laminated plates on the bearing strength and failure mode, parametric analyses were carried out, experimentally.

Sayman et al.[21] worked to characterize the bearing strengths of mechanically fastened joints with single bolt in glass–epoxy laminated composite plates experimentally. The effects of different geometrical parameters on failure behaviors were also examined. Ryu et al.[22] have examined failure load using linear finite analyses in mechanically fastened composite joint and compared their results with experiments. Kweon et al. [23] conducted a two-dimensional progressive failure analysis to predict the failure loads and modes of uni-directional-fabric laminated composite joints under pin loading by applying a two-dimensional progressive damage analysis program (ACOS-J). They also studied the effect of various failure criteria and have shown that a finite element analysis based on the combined Yamada–Sun and Tsai–Wu criteria accurately predicted the failure loads of the composite laminated joints. Dano et al.[24] carried out analysis of bolted joints in composite laminates and proposed the strains and bearing stiffness predictions.

2008- Barut, Madenci et al.[25] developed a semi-analytical method for the coupled in-plane and bending analysis of composite bonded–bolted single-lap hybrid joints. The laminate and bolt displacements are based on the Mindlin and Timoshenko beam theories, respectively. The bending is mainly due to the force couples created by the lap geometry. The laminates are joined through an adhesive bond layer along the overlap region between the laminates and a pre-tensioned bolt placed right at the centre of the overlap region. The present analysis results show that the clamp-up force induced by the bolt stretching applies compression to the laminates through the bolt heads, causing compressive peeling stresses around the bolt head regions. Choi et al.[26] have used the failure area index (FAI) method to predict the failure load of a composite joint subjected to a clamping force. The test and analysis results showed the failure load of a mechanically fastened composite joint subjected to a clamping force could be predicted within 23% via the FAI method. Regarding more efficient design practices, simplified finite element models have been proposed in the past. One such technique used linear beam elements to model the fastener and shell elements to model the composite plates. Coupled with a simplified contact model, the method was used to simulate the load distribution in a multi-row, multi-column joint and good agreement was obtained when compared to an experimental test. However, this model omitted important joint parameters, such as friction between the laminates. This issue was later addressed by Ekh and Schön et al. [27], who used beam elements to model both the bolt and the laminates, while bolt-hole clearance and friction effects were captured through the use of connector elements. While excellent agreement was obtained with experimental and numerical results, this approach was limited to single-column joints.

Sayman and Ahishali et al.[28], have carried out an experimental failure analysis on mechanically fastened joints in composite laminate under 2.5 and 5 Nm compressive preload moments. Karakuzu et al. [29,30] studied the effects of geometrical parameters such as the edge distance-to-hole diameter ratio (E/D), plate width-to-hole diameter ratio (W/D), and the distance between two holes-to-hole diameter ratio (M/D) on the failure loads

and failure modes in woven glass vinyl ester composite plates with two serial and parallel pin loaded holes. They conducted experiments and numerical analysis using LUSAS, commercial finite element software by employing Hashin failure criterion. After experimental and numerical studies they showed that the ultimate load capacity of woven glass–vinyl ester laminates with pin connections increased by increasing ratios E/D, W/D, and M/D. As mentioned above, much of the previous studies on mechanically fastened composite joints have been carried out at room temperature except for a few of them, such as the work done by Song et al. [31] , a study, aimed to investigate the bearing strength of a blind riveted single lap joint of a carbon/epoxy composite after heat exposure . Sen et al. [32] analyzed failure of mechanically fastened joints with clearance in composite laminates under preload. The research focused on the failure experiments of composite mechanical fasten joint, the influences of clearance on failure load and failure mode.

2009- Sen and Sayman et al.[33] performed an experimental failure analysis for two serial bolted composite plates. The composite plates were produced from eight laminas and glass fibres were used as reinforcement material with epoxy matrix. The effect of material parameters and design parameters was considered. Hongshuang et al.[34]worked on the probabilistic strength analysis of bolted joint in laminated composites using point estimate method. Francesco et al.[35] carried out an experimental investigation on the bearing failure load of glass fibre/epoxy bolted laminates. Barut and Madenci [36] developed a semi-analytical solution method to analyze stress of single lap hybrid (bolted/bonded) joints of composite laminates under in-plane and lateral loading. The comparison of the results proved the robustness and accuracy of this approach in capturing the correct response of the contact stresses in the bolted joint analysis and adhesive shear and peel stresses in the bonded joint analysis.

2010- Kapti et al.[37] investigated the effects of preload moment, moisture and interference-fit on bearing strength and failure mode in pin-jointed and bolted carbon–epoxy plates which were subjected to a traction force. The test results showed that the ultimate failure loads were directly affected by the geometrical parameters, preload moments and interference-fit. The effects of seawater on failure modes and loads were studied. For the specimens in wet condition, failure loads increased with preload moments while failure loads stayed almost the same in non-preloaded specimens. Tsai-Wu criterion was used to determine bearing strength corresponding to first failure load. It was concluded that the numerical results are in good agreement with experimental results. McCarthy and Gray et al.[38] presented the development of an enhanced analytical approach for modelling non linear elastic behaviour of multi-bolt composite joints. The model is a closed-form extension of a spring-based method, where bolts and laminates are represented by a series of springs and masses as shown in fig.3. The method is validated against detailed three-dimensional finite element models and where possible, experimental results. The effect of varying bolt-torque and bolt-hole clearance, friction on the load distribution in a three-bolt, single-lap joint is investigated and the method proves to be robust, accurate and highly efficient. Finally, the method is employed in a parameter study, where increasing bolt torque levels can be used for achieving a more even load distribution in multi-bolt joints. The main limitation of this approach is that multicolumn joints cannot be analysed, where any number of bolts may be present in both in-plane directions.

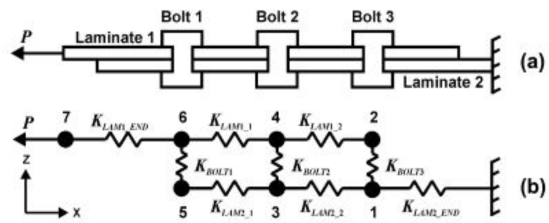

Fig. 3. Three-bolt, single-lap joint: (a) illustration; (b) corresponding spring/mass system.

Ozen and Sayman et al.[39] studied the failure loads of fibre glass–epoxy prepegs laminates with two serial holes using experimental and finite element analysis. Tsai–Wu failure criterion was used to predict first failure loads by finite element analysis for the geometrical parameters-edge distance-to- upper hole diameter (E/D), the distance between centre of two holes-to-hole diameter (K/D), and the width of the specimen-to-hole diameter (W/D) as shown in fig.4. An experimental investigation was carried out to see the effects of preload moments and sea water on the bearing strength of joints. It was observed that the immersion of test specimens into sea water causes a decrease in the failure load without a preload moment. The test specimens under preload moments produce nearly the same bearing strength as unimmersed specimens. Francesco et al.[40] presented an experimental analysis on the influence of bolt diameter for glass fiber reinforced polymer (GFRP) bolted laminates. In that study they tested three different types of laminates: one was mono directional while the other two were bi-directional, with two different stacking sequences. They found that reductions in the pin-bearing ultimate load were linearly dependent on bolt diameter. They also proposed a pin-bearing design formula based on their experimental results. McCarthy et al.[41] used a global bolted joint model (GBJM) and an analytical model to investigate the bolt–hole clearance, bolt-torque, friction between laminates, secondary and tertiary bending in the laminates as well as the load distribution in multi-bolt joints, respectively. Since GBJM simplified the simulation, so the GBJM was found to be robust, accurate and highly efficient, with time savings of up to 97% realized over full three-dimensional finite element models. The analytical model was validated against detailed three-dimensional finite element models and experimental results. An artificial neural network (ANN) method was developed by Sen et al.[42] to predict the bearing strength of two serial pinned/bolted E-glass reinforced epoxy composite joints. The experimental data with different geometrical parameters and under various applied torques were used for developing the ANN model. Comparisons of ANN results with desired values showed that ANN is a valid powerful tool to prediction of bearing strength of two serial pinned/bolted composite joints.

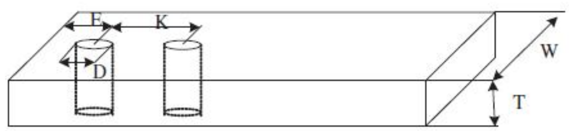

Fig.4.geometric parameters of laminate.

2011- Research in the field of bolted joints has mostly concentrated on straight shank bolts, with limited work on countersunk bolted joints. Chisti et al.[43] conducted an experimental investigation into the damage progression and strength of bolted joints with fibre-reinforced composite laminates and countersunk fasteners. The main goal of the experimental investigation is to characterise the effect of the countersink geometry on the load-carrying capacity of single lap joints in comparison to the straight-shank case. It is found that introduction of the countersunk hole roughly halves the bearing stress, and causes delamination for some configurations. This delamination is primarily located at the start of the countersink region, though is found to be triggered by other damage mechanisms and has only minor influence on the results. Bolt torque increases the density of through-thickness damage though limits its extension from the hole edge, whilst bolt clearance causes localisation of the damage region. Increasing the ratio of the countersink depth to the laminate thickness reduces the extent of bearing and promotes bending, with a change to net section failure at large ratios. Wang et al.[44] used XFEM to calculate the failure load of joint. Compared with experiment result, the error of simulation result calculated by XFEM is about 12.7%. The simulation result is verified by the experiment. XFEM has better accuracy and versatility by using three types of mesh size and two different stacking sequences. To simplify calculation of XFEM model, composite laminates of joint are modelled using linear elastic properties. Three-dimensional equivalent material properties are calculated by the MATLAB code written by author. The crack initiation and propagation are tracked easily and clearly by XFEM and progressive damage of laminate is observed. Failure mode of joint can be observed by XFEM. The influences of geometric parameters on failure load and bearing strength of joints are investigated.

It has been found that an increment in the tightening torque has two important effects on the joint performance. The positive effect is the increment of friction forces that lead to increasing bearing strength. On the other hand, the negative effect is that out-of-plane stresses can lead to a premature failure of the joint . In consequence, the maximum value of torque is limited by standards. This was found by Santiuste et al.[45] when working on the computational analysis of temperature effect in composite bolted joints. Sen and Sayman et al.[46] investigated the effects of material parameters, geometrical parameters and magnitudes of preload moments on the failure response of two serial bolted joints in composite laminates. Some geometrical ratios were found out to be unfavourable and the increasing of preloads was seen very convenient for safe design of two serial bolted composite joint.

2012- A new set of failure criteria is proposed by Olmedo and Santiuste et al.[47] to predict composite failure in bolted joints. The present failure criteria include out-of plane shear stresses in the formulations of the four failure criteria proposed by Chang–Lessard and the consideration of two new failure modes: out-of-plane matrix cracking and delamination. The advantages of the present failure criteria with respect to Chang–Lessard criteria are the consideration of a 3D stress field and the prediction of out-of-plane failure modes as delamination. The main advantage with respect to others 3D failure criteria as Hashin is the inclusion of non-linear shear stress–strain relationship. These advantages are especially useful to predict bearing failure in bolted single-lap composite joints because the present model can take into account the out-of-plane stresses produced by torque tightening and the 3D stress field induced by secondary bending. The results were also compared with those obtained using classical 3D failure criteria as Hashin. The maximum load predicted by the present failure criteria was lower than that predicted by Hashin because of the consideration of non-linear shear stress–strain relationship. Hashin criteria overestimated the stiffness and the bearing strength of the joint. Egan et al.[48] during his stress analysis of single-bolt, single-lap, countersunk composite joints with variable bolt-hole clearance found that secondary bending produce non-uniform stress distributions through the thickness of composite laminates in the vicinity of the bolt hole. An experimental failure analysis has been carried out by Soykok et al.[49] to determine the effects of thermal condition and tightening torque on the failure load and failure behavior of single lap double serial fastener glass fiber/epoxy composite joints. 40, 50, 60, 70, and 80 degree Celsius temperatures were exposed to the specimens during tensile tests. It was seen that, the load-carrying capacity of the joint is decreased gradually by increasing temperature level. Zhou et al.[50] investigated the influence of geometric parameters on failure response of bolted single-lap composite joints by experiments and finite element methods. Since VARI process cures in room temperature and enable the manufacture of large structures with high mechanical properties under vacuum. So VARI is chosen as the moulding process of specimens in experiments. To predict failure of joint, two kinds of progressive failure models are developed in ABAQUS, using subroutines USDFLD and VUMAT, respectively. Simulation results show an excellent agreement with experimental results. Failure model developed in ABAQUS/Explicit was found to be robust, accurate and highly efficient.

III. CONCLUSION

Vast researches have been done on mechanically fastened joints with different parameters such as material and geometrical properties together with a one or a combination of failure criterion to predict the failure load and failure mode, on the strength of the joint by experimental, analytical and numerical means. As mentioned above, much of the previous studies on mechanically fastened composite joints have been carried out at room temperature .The analytical method has proven to be accurate and robust when compared to numerical and experimental studies on single-lap joints. Although the experimental studies can give both the stiffness and strength of the composite joint, it cannot give the detailed stress information in the structure. Besides it is very costly to perform a great amount of experiments. Hence, analytical and numerical methods become very important. In order to alleviate extensive computations in the case of a bolted or bonded joint analysis, semi-analytical methods exist to predict the stress field in both bolted and bonded lap joints. In contrast to the considerable literature available on straight shank bolts, the literature with regards to countersunk joints is not as comprehensive. A few investigations have focused on the contact condition of the bolt , or the application with multi- bolt joints . These investigations have typically focused on describing the joint behaviour using the load history, and detailed microscopy of countersunk joints under a range of joint configurations have not been published in open literature. Further, the majority of literature on composite bolted joints relates to unidirectional tape material, and the damage mechanisms and joint behaviour of laminates manufactured using fabric plies have not been reported. Research on the influence of bolted joint parameters on the joint strength and damage progression has also been dominated by investigations into straight-shank bolts. Bolt torque has been investigated by several authors for straight-shank bolts and found to increase bearing and failure loads, as well as limit delamination. Clearance in straight-shank bolt holes has been found to reduce the bolt contact area, affecting the load transfer, high stress regions and joint bearing loads All above-mentioned finite element methods make some progress on prediction properties of composite and can simulate the failure of composite, however these methods still need to be improved.

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