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Failure Stress Correlation of Composite Laminates Containing a Crack

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Loss of residual strength is analytically evaluated for composite material containing structural damage in the form of a crack. The assessments are conducted using a Lockheed-developed anisotropic crack-tip element to determine the applied stress intensity level in a cracked panel. Analysis procedures are used in conjunction with basic materials property data to predict failure stress conditions for AS/3501-6 graphite/epoxy panels. Over 100 residual strength tests were conducted on 16-ply laminates covering a broad range of ply orientations to provide a wide variation in residual strength behavior. Good correlation was demonstrated between experimental results and analytical predictions.

Background

A PRIMARY concern in the development of all aircraft structures is providing for the durability and damage tolerance of the system. These aspects of the design are of concern from the standpoint of the safe and economic use of the structure. Safety in flight and low maintenance cost are extremely important factors which must be considered in the early design stages in order to achieve the desired objectives without compromising the efficiency of the structure or leaving the attainment of the goal to chance. Specific requirements have been formulated to control the incorporation of these qualities in the design of metal aircraft structures. The detail requirements for military aircraft are documented in MIL-STD-1530A, MIL-A-83444, MIL-A-008866B, and MIL-A-008867B. Although these criteria are specifically identified as applicable to metal structure, the objectives of the criteria are general in nature and would apply to any type of structure, including composite structure. To some extent, even the basic approaches encompassed in the detail criteria can be applied in the development of a composite design. These comments are not intended to imply that there are no unique problems associated with a composite design. A review of the fatigue and fracture behavior of composite structure, including the influence of cracks on compressive as well as tensile residual strength, clearly indicates a present need for a durability and damage-tolerance structural requirements document comparable in scope to the criteria specified for metal structures.

Introduction

In general, composite structures have been found to exhibit good fatigue properties, that is to say, good endurance in terms of time to crack initiation. However, as in the case of metals, a distinction must be made between the fatigue and the damage-tolerance capability of the structure. One of the more important elements in any assessment of damage tolerance is the residual strength of the damaged structure. This paper addresses the loss of residual strength in a composite material associated with structural damage in the form of a crack.

The presence of a crack in a composite material can cause a loss in strength that is significantly disproportionate to the loss in area associated with the crack. Therefore, as in metal structures, it is essential that analytical methods be developed for composites to permit the incorporation of appropriate levels of damage tolerance as an integral part of the design development process. In support of this objective, Lockheed has developed an anisotropic crack-tip element[1] that can be used with general finite-element methods of stress analysis to determine applied stress intensity levels in a loaded panel containing a crack. The analytical approach was used in conjunction with basic material property data[2-4] to predict failure stress conditions for AS/3501-6 graphite/epoxy panels. Unstable crack growth in the panel is predicated on the applied stress intensity reaching the allowable fracture toughness of the material.

Experimental Program

To verify the results, residual strength tests[2] were conducted on 16-ply laminates covering a broad range of lay-up or ply orientations to provide a wide variation in residual strength behavior. A total of 123 test specimens were included in the residual strength program. Additional specimens were tested to establish basic material property data. All analyses and tests were performed on simple panels of configuration and loading, as shown in Fig. 1. These specimens are 3 in. wide and 12 in. long. It can be seen that two crack con-

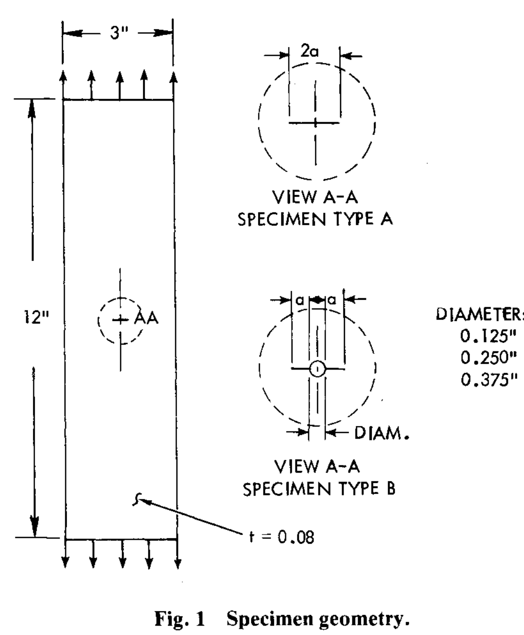

Fig. 1 Specimen geometry.

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Table 1 Fracture toughness and stiffness matrix

Laminate lay-up	Fracture toughness K_c, ksi-$\sqrt{\text{in}}$.	Elastic constants, 10^6 psi A_{11}	A_{12}	A_{22}	A_{66}
$[0/\pm45/0]_{2s}$	33	13.8000	2.7914	4.1153	3.0831
$[0/\pm45/90]_{2s}$	24	8.9576	2.7914	8.9576	3.0831
$[0/\pm45/\pm45/0/\pm45]_s$	29	10.1620	4.0079	5.3199	4.2996
$[0_2/\pm45/0_2/90/0]_s$	44	15.0160	1.5748	5.3318	1.8665

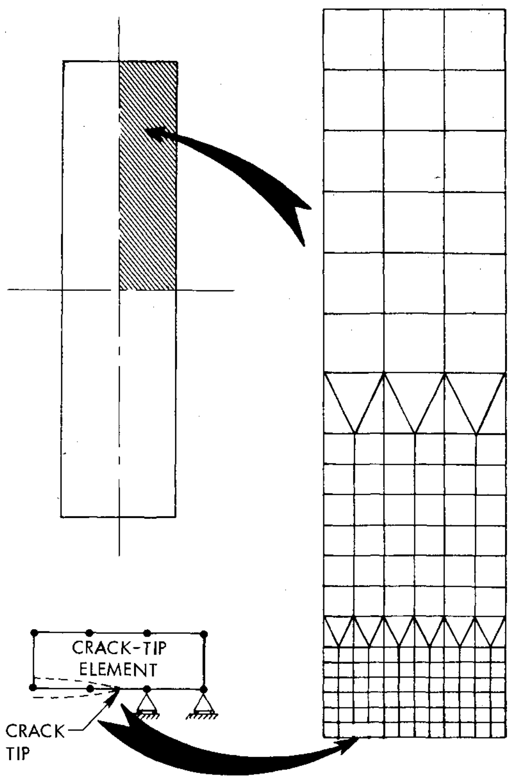

Fig. 2 Finite-element model.

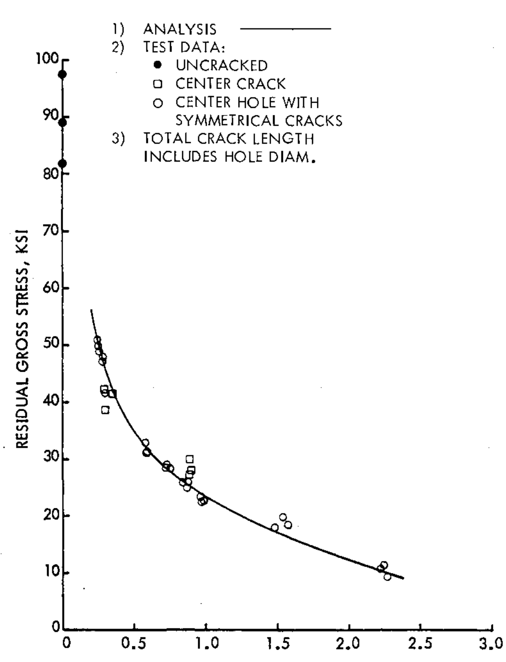

Fig. 3 Residual tensile stress of graphite/epoxy laminate, $[0/\pm45/0]_{2s}$.

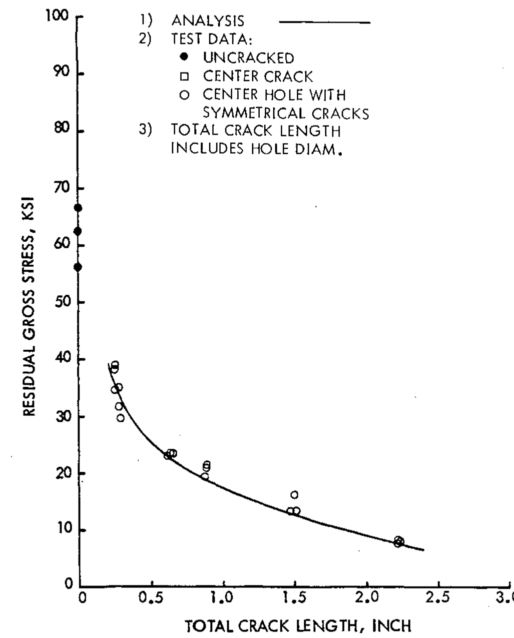

Fig. 4 Residual tensile stress of graphite/epoxy laminate, $[0/\pm45/90]_{2s}$.

figurations were considered, that is, through-the-thickness cracks emanating from a centrally located circular hole, and a centrally located through-the-thickness crack. In most cases, the hole diameter was 0.25 in.; however, a few specimens with 0.125- and 0.375-in. diameters were also tested. The majority of the tests were performed on specimens containing holes; but, only the specimens without the hole were used to establish the fracture toughness of the multiple angle-ply composite laminates. Table 1 lists the lay-up of the primary laminates treated in the program and the corresponding fracture toughness, along with the elastic constants which relate panel stresses and strains. The test data are used to evaluate the degree of correlation between experimental results and analytically predicted values.

Analysis Approach

As previously noted, the fracture analysis is based on a finite-element treatment of the panel. Figure 2 shows the basic finite-element model used in these assessments, including a description of the crack-tip element for symmetrical cases. A crack-tip element for unsymmetrical loading or geometry conditions is also available for general applications in the analysis of complex structures. Developed substructuring and coupling procedures can be used in conjunction with the general internal loads and stress analysis to evaluate the fracture behavior of any local area or structural arrangement in a composite or metal/composite design.

Four basic laminate lay-up configurations were selected to evaluate the capability of reasonably predicting the fracture strength of cracked composite materials. Initial plans were to use the simple center-cracked specimens to determine the fracture toughness of each laminate lay-up and to sub-

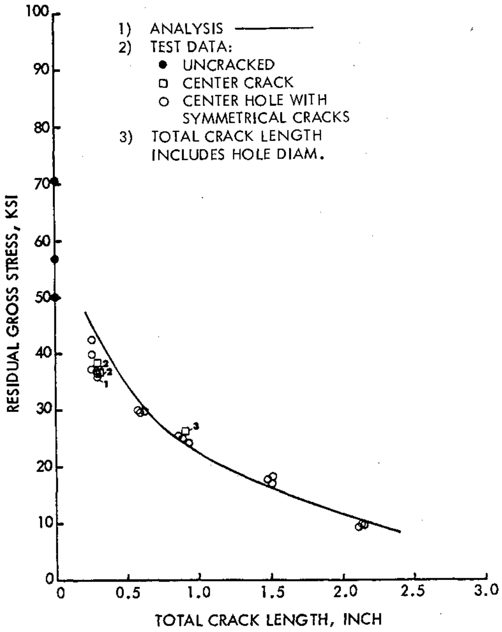

Fig. 5 Residual tensile stress of graphite/epoxy laminate, $[0/\pm45/\pm45/0/\pm45]_s$.

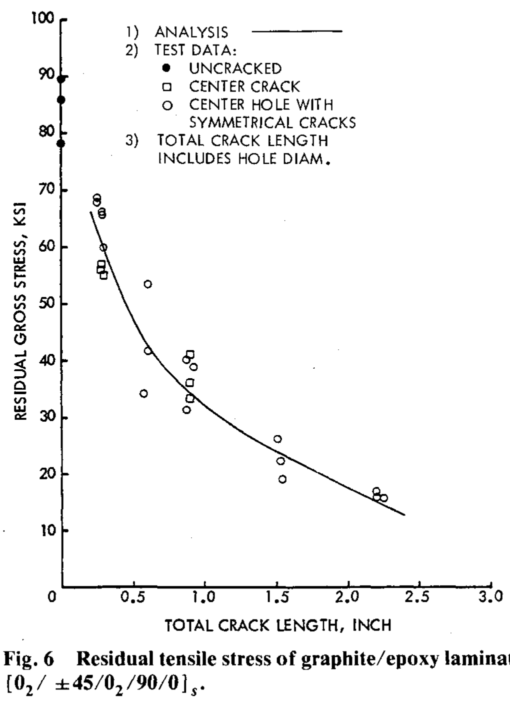

Fig. 6 Residual tensile stress of graphite/epoxy laminate, $[0_2/\pm45/0_2/90/0]_s$.

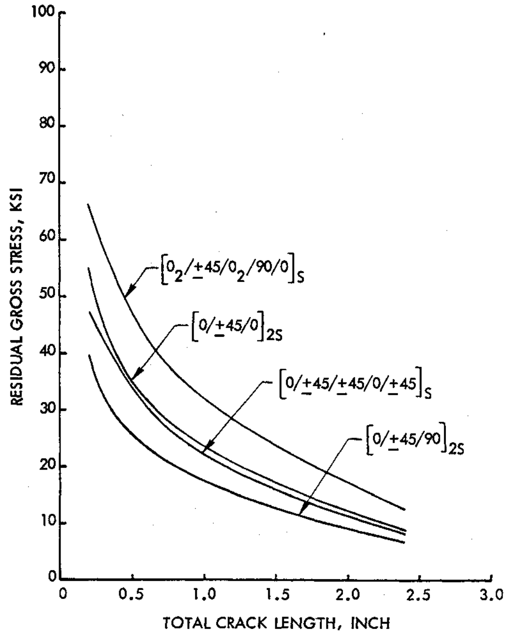

Fig. 7 Residual tensile stress of graphite/epoxy laminates—summary results.

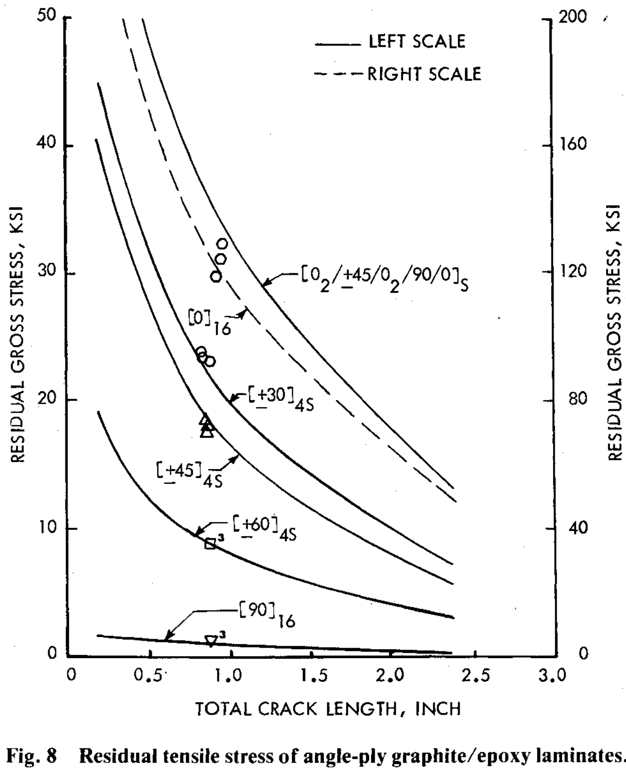

Fig. 8 Residual tensile stress of angle-ply graphite/epoxy laminates.

sequently evaluate the residual strength of the panels, including hole effects. A hole element was to be used with crack-tip elements for these assessments. However, it was found that the hole effect was not fully developed in the fracture behavior of the composite panels. As a result, specimens with cracks emanating from a center hole are treated without regard to hole effects. The total crack length in these analyses represents the sum of the crack lengths and hole diameter. All three hole diameters considered in the program indicated similar characteristics.

Analysis and Test Correlation

Typical results are shown in Fig. 3 for a $[0/\pm45/0]_{2s}$ laminate. It can be observed that three specimens were tested for each crack configuration. Average fracture toughness, K_c, for the simple center-crack specimens is used to develop the full curve for the predicted residual strength of the panel. Two crack lengths were used for establishing this parameter for the particular laminate lay-up. The determination of fracture toughness in these cases is based on the anisotropic solution. Scatter was minimal in the experimental results and good correlation is indicated between the analytical curve and the test data points. In general, greater scatter was observed in the uncracked specimens than in those containing cracks. The plotted data also show the small and often inconsistent influence of the hole on the fracture behavior of the panels. Figures 4-6 present similar comparisons for $[0/\pm45/90]_{2s}$, $[0/\pm45/\pm45/0/\pm45]_s$, and $[0_2/\pm45/0_2/90/0]_s$, respectively.

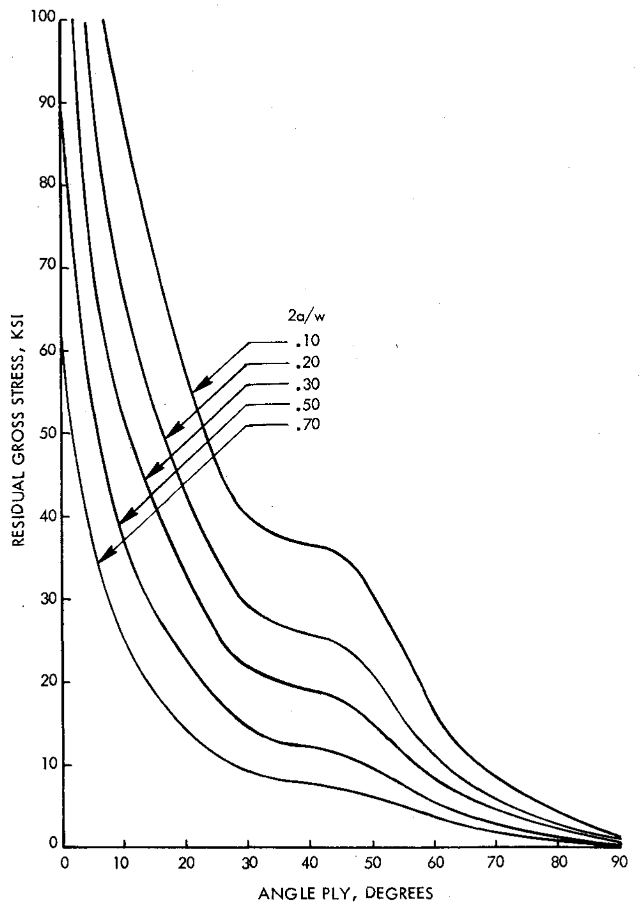

Fig. 9 Influence of ply orientation on residual tensile stress of graphite/epoxy laminate.

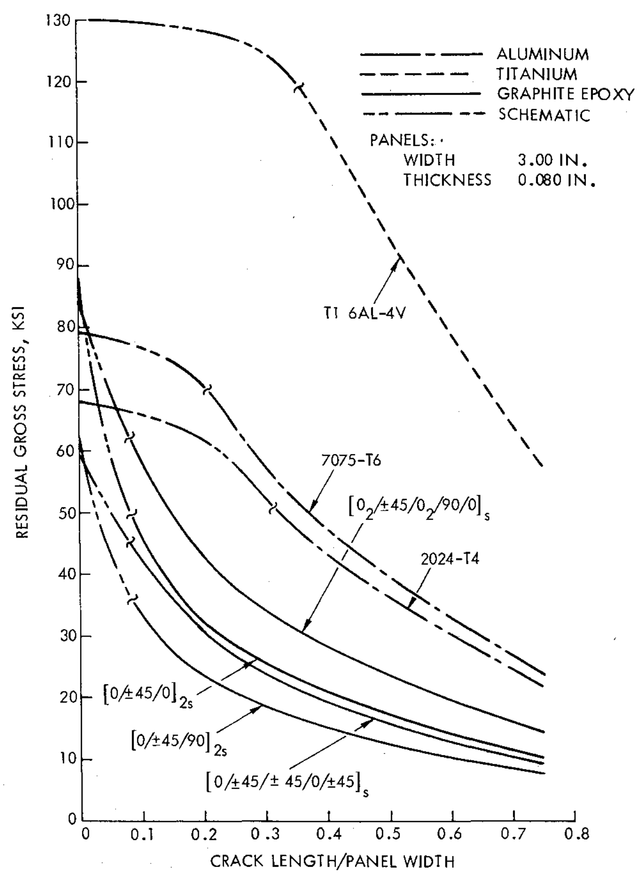

Fig. 10 Residual strength of unstiffened flat panels.

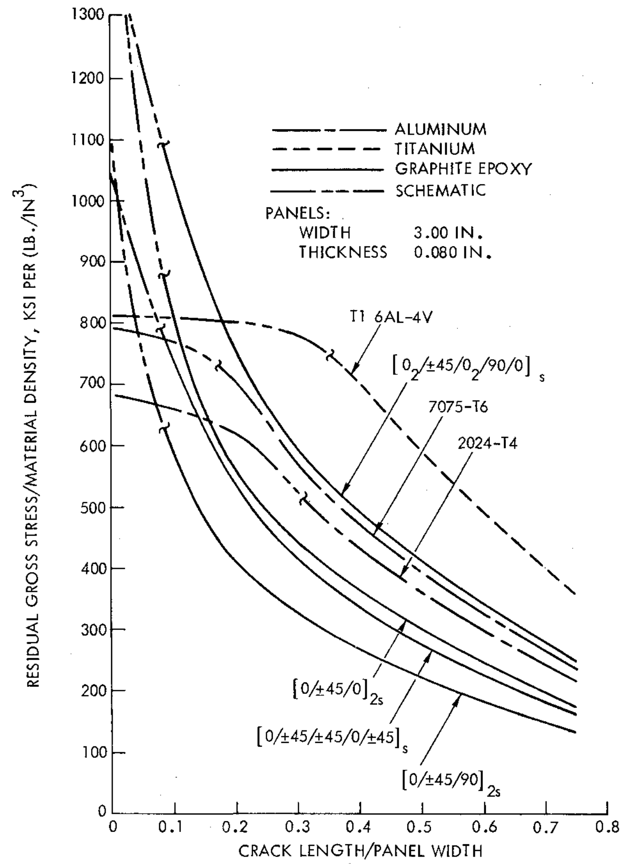

Fig. 11 Residual strength of unstiffened flat panels: strength-to-weight ratio.

A summary of the residual strength curves for all of the laminate lay-ups is given in Fig. 7. The results show the heavy influence of the 0-deg plies in resisting fracture from cracks lying in a plane normal to the fiber orientation. In order to further evaluate the influence of fiber orientation on fracture strength, tests and analyses were conducted on angle-ply graphite/epoxy laminates. As in the basic program, all panels were 16-ply laminates. The analytical residual strength curves and the test data points are presented in Fig. 8. These results present a quantitative assessment of the influence of ply orientation on the fracture behavior of composites. It shows the overwhelming influence of the 0-deg plies in determining the fracture toughness characteristics of the laminates considered in the basic program. The residual strength curve for the $[0_2/\pm45/0_2/90/0]_s$ laminate lay-up is shown for reference purposes. Figure 9 is a crossplot of the data in Fig. 8 and shows the rapid reduction in residual strength as the orientation of the fibers and the crack deviate from perpendicular. The figure also shows that residual strength properties are somewhat uniform for fiber orientations between 30 and 45 deg. Beyond this point, residual strength deteriorates rapidly.

Concluding Remarks

A final comparison is made to show the relative performance of the composite laminates and some typical metallic materials in terms of their fracture behavior. Results for mixed mode fracture conditions corresponding to a panel thickness of 0.080 in. are shown in Fig. 10. It can be observed that on the basis of absolute strength, the residual strength of the composite laminates is generally lower than for the selected metallic materials. Beyond the yield stress or test data coverage, the curves have been extended schematically to illustrate the relative performance of the panels from both the standpoint of fracture and the static tensile strength of the materials. The purpose is to show the rapid rate of decline in tensile strength associated with the presence of through-the-thickness cracks, particularly in the case of the composite laminates. Figure 11 presents a similar comparison in terms of strength-to-weight ratios. From the standpoint of uncracked structure, these data show that the composite laminates are clearly superior to the metals; however, for progressing crack lengths, the trend is generally reversed. It can be seen that design damage-tolerance requirements have an important bearing on the material selection process. In any case, the conclusion to be reached on the basis of these results is that residual strength must be addressed in the design and development of composite aircraft structures. For a given level of exploitation of static strength properties, critical crack lengths in composite materials under limit load conditions can pose a difficult detection problem from the standpoint of inspection. The analytical approach for evaluating the fracture behavior of composite materials followed in this program provides a suitable means for treating the problem during the development of new designs. Implementation of this analysis capability presents minimal difficulty since finite-element analysis procedures are in general use throughout the industry.

References

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