Design and Analysis of Integrally Stiffened Metallic Panels and Riveted Stiffened Metallic Panels

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Abstract*—Riveted stiffened panels are in use since the beginning of aerospace industry. This technology has been through continuous development and improvement and has limited scope for further improvement. On the other hand integral stiffening is a relatively new technology and has better prospects in terms of static strength and weight. The advancement in high speed machining has made it possible to manufacture integrally stiffened panel at rapid rates. This advancement in production capability and several other benefits such as reduction in number of parts, smooth exterior surface, elimination of sealing problems etc. has made the feasibility study of integrally stiffened panels an extremely important research area. Although integrally stiffened panels have several advantages, their practical application is limited due to lack of damage tolerance behavior of these panels. Considering the capability to predict accurate results using FEM and FEA as compared to analytical methods, the static strength and damage tolerance analysis of both types of stiffened panels are performed for different shapes of stringers. Von misses stress criteria is used to compare static structural strength and SIF is used to perform the crack growth rate analysis in AFGROW to compare the damage tolerance strength. The results show that the integrally stiffened panels have better static strength and lesser weight as compared to riveted stiffened panels, but the riveted stiffened panels have better damage tolerance capability. Therefore, further improvement in damage tolerance of integrally stiffened panels should be undertaken.

Keywords*—Integrally Stiffened Panels, Riveted Stiffened Panels, Damage Tolerance Analysis, FEM, FEA, Stress Intensity Factor (SIF), Crack Growth, ANSYS, AFGROW.

I. INTRODUCTION

The aircraft have been designed by skin-stringer assemblies since 1940's. Mainly the wing, fuselage, and empennage are made from metallic stiffened panels [1]. The stringers in these panels prevent buckling from shear and compressive loads, carry bending loads and inhibit crack growth by providing alternate load path [2]. This technique has undergone extensive improvement and maturity. Further development in this technique is not possible without major design variations [3, 4]. Integral stiffening technology is an alternative technology which is comparatively new and has a vast scope for development and maturity in the near future.

Currently there are three types of skin stringer panels riveted, integral, and bonded. The integral panels can be manufactured by different techniques such as high speed machining (HSM), Laser Beam Welding (LBW), and Friction Stir Welding (FSW). Reference [5] investigated the optimized processing routes and new alloy chemistries in order to improve the fatigue, residual strength and fracture toughness of the material and the joints .In our analysis we are considering integrally stiffened panels made from HSM only.

The integral panels require lesser number of components and are comparatively smoother, thus it is easier to perform visual inspection [2]. In addition, enhancement in high speed machining capabilities and the requirement of reduced manufacturing cost has made the feasibility study of integrally stiffened panels an important consideration [4]. The primary objective of this study is to validate equal or better performance than conventional designs with regard to weight, structural integrity, and damage tolerance while achieving a significant reduction in manufacturing cost. However, lack of damage tolerance capability of integrally stiffened panels has limited its large scale application in damage tolerance critical areas such as fuselage.

Different design optimization techniques are under progress to increase the damage tolerance capability of integrally stiffened panels. Hybrid design, with composite material strips bonded to the panel has given significant improvement in damage tolerance of integrally stiffened panels [6]. Similarly, Crack turning is identified as an important phenomenon to improve the residual strength and damage tolerance of integral structures. But the reduction in crack turning in the presence of Multiple Site Damage(MSD) has questioned its reliability [7].

Several methods are available to calculate SIF and life prediction but they are based on inaccurate assumption that the crack growth rate is same in the skin and the stringer, as identified by Zhijun Shi. Therefore, a new iterative method was proposed to calculate SIF which provides more accurate results but takes more time as compared to existing methods [7]. Muhammad Adeel Compared Stress intensity factors and fatigue crack propagation rates of both types of stiffened panels using FEM. Only Z shaped stringers were used in the analysis. He concluded that integrally stiffened panels have higher stress intensity factor than conventional stiffened panels which means the crack growth rate is greater in integrally stiffened panels [8]. A. Brot et al. experimentally tested three integrally stiffened panels and verified that integrally stiffened panels lack damage tolerance. Therefore, they tested a new hybrid design in which carbon epoxy stripes were bonded to the panels. Significant reduction in the stress intensity factors was obtained but the researchers realized that due to the difference in thermal coefficient of the strips, residual stresses are generated in the panels at extreme temperatures. Therefore, this design technique needs further testing and development [6]. R. G.Pettit et al. tested and compared different manufacturing techniques and processes of integrally stiffened panels and concluded that high speed machined plate hog outs are more economical as compared to the extruded panels[4].

In this paper comparison of static strength and damage tolerance of riveted stiffened metallic panels and integrally stiffened metallic panels has been carried out. Static strength analysis and SIF's are calculated in ANSYS. The SIF's were used in AFGROW to perform the damage tolerance analysis.

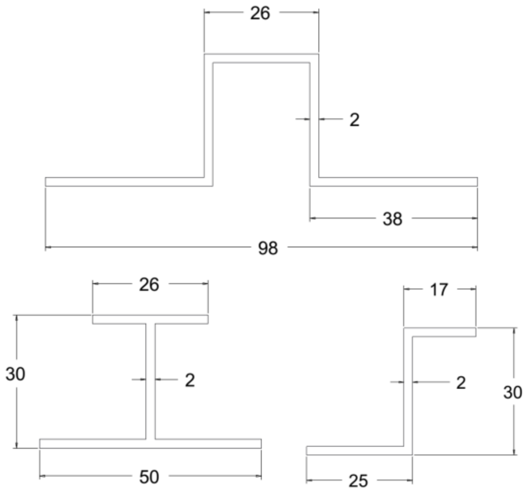

Fig. 1 Dimensions of the models

II. Finite Element Modelling

The riveted and integrally stiffened panels are modeled in CREO. A total of six models are made in which three different shapes of stiffeners are used i.e. Hat shape, T shape and Z shape for both types of panels. Each plate is stiffened with 2 stringers. The stringer pitch is 200 mm. The width and length of the panels are 500 mm and 317 mm respectively. In riveted stiffened panels, stringers are attached to the skin by row of rivets with the pitch distance of 20 mm and the diameter of 6 mm. In integrally stiffened panels, the stringers are integrally machined with the skin. These models are imported to ANSYS workbench and static structure analysis is performed using static structure module. Finite Element Analysis is performed to determine the Von Misses stresses, deflection and Stress Intensity Factor (SIF) of each stiffened panel.

For riveted panels, bonded contact is used between the stringer and rivets, and skin and rivets with pure penalty formulation which provides large normal stiffness with a very small penetration between nodal geometries and high chances of convergence with less number of iterations. As a result, they are bonded like glue with no relative motion. The no separation contact with pure penalty formation is used between the skin and stringers because of the small relative sliding with each other. In Integrally stiffened panels, the skin and stringers are modeled as a single body.

A. *Meshing*

The solid 185 element is used to model the stiffened panels. For riveted panels, the skin and stringers are meshed with hexahedral elements of 3 mm. For refinement, 10 inflation layers of 0.05 mm thickness are generated around the rivet holes to capture the stress gradient where the stress concentration is higher as shown in Fig. 2. Curvature normal angle of mesh around the curvature is adjusted to 20 degree and size mesh is 0.2 mm. It results in a good quality finer mesh around the rivets and gives accurate stresses. Rivets have high curvature so tetrahedral mesh of 0.2 mm is created on rivets. For integral panels, the volume mapped face mesh of 3 mm is generated on the surface of the skin and stringers. It generates structured hexahedral mesh.

In the initial numerical simulations, the test panel FE models are fixed in all degrees of freedom at one end. The left and right sides are constrained in x direction (normal to the surface). These boundary conditions are expected to generate stiffer behavior due to the absence of the surrounding structure. The uniform longitudinal stress of 100 MPa is applied on the other end in the direction of stringers as shown in Fig. 4. Longitudinal stress is produced in the wall when a thick-walled tube or cylinder is subjected to internal and external pressure. The longitudinal stress can be expressed as:

$$\sigma = (p \times r)/(2 \times t)$$

Where "σ" is the longitudinal stress, "r" is the radius, "p" is the pressure and "t" is the thickness of the cylinder.

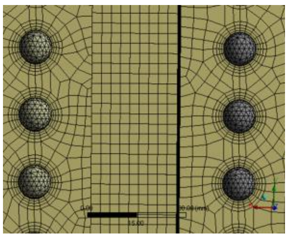

Fig. 2 Meshing of Riveted panel

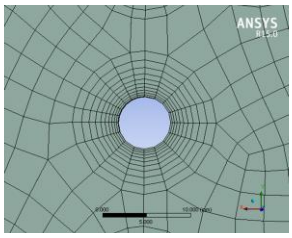

Fig. 3 Meshing of rivet hole

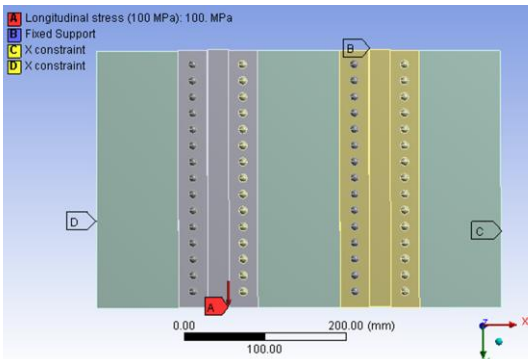

Fig. 4 Model of hat riveted stiffened panel

III. Finite Element Analysis

The linear analysis is performed on all stiffened panels. The von-misses stresses and deflection are calculated for each panel. The graph is plotted between maximum stress and load for comparison. The failure of stiffened panels is analyzed by comparing the localized maximum stresses to the ultimate tensile strength of the material as shown in Fig. 7. The deflection comparison between the stiffened panels is shown in Fig. 6. For Stress Intensity Factor, the circumferential crack is initiated in the center of the skin for both types of stiffened panels. The quarter 3D sub-model is considered for calculating stress intensity factors. Same loading condition is applied and the linear elastic analysis is done on 3D-sub models for different crack lengths. Boundary conditions and the loading conditions for the quarter 3D panel is shown in Fig. 4. The graph of Stress Intensity Factor (K_I) vs. half crack length (a) is plotted for both types of stiffened panels as shown in Fig. 9.

IV. Results

Three things were compared in the static strength analysis of both types of stiffened panels i.e. maximum deflection, maximum stress and mass. The comparison of the results of the deflection, stress and mass are shown in the graphs. The maximum stress is obtained around the rivet holes. The maximum stress is same for all types of riveted stiffened panels which means that maximum stresses is independent to the shape of stringers in riveted stiffened panels. The integrally stiffened panels have higher strength and lesser mass as compared to riveted stiffened panels. However the integrally stiffened panel lack the load bearing capability in the presence of crack as shown Fig. 9 [4, 8]. Both types of panels show the same result when the crack tip is far from the stringer. When the crack tip passes through the stringer, the stress intensity factor K_I for riveted panel decreases while in the integral panel increases .The hat riveted stiffened panel has lowest stress intensity factor values which means they have high damage tolerance capability.

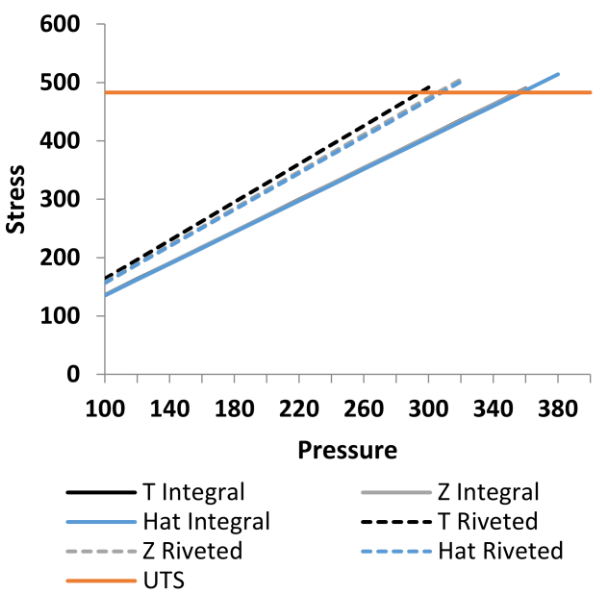

Fig. 5 Stresses at different pressures

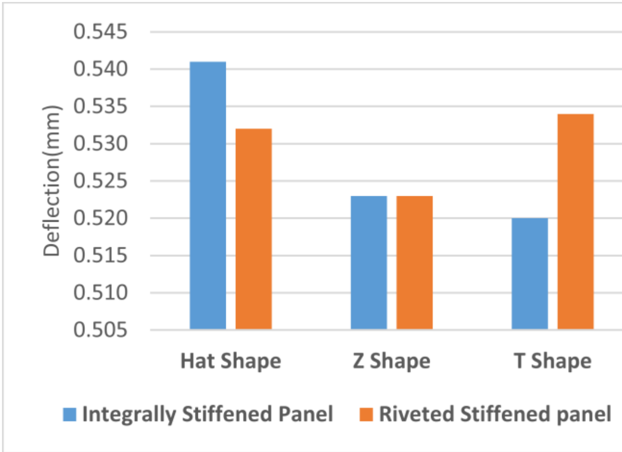

Fig. 6 Comparison of maximum deflection

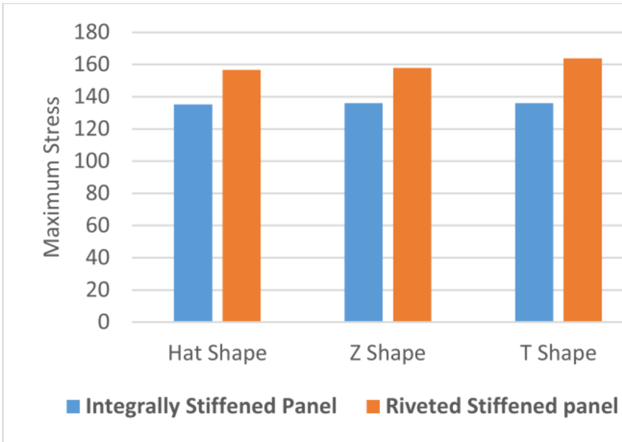

Fig. 7 Comparison of maximum stress

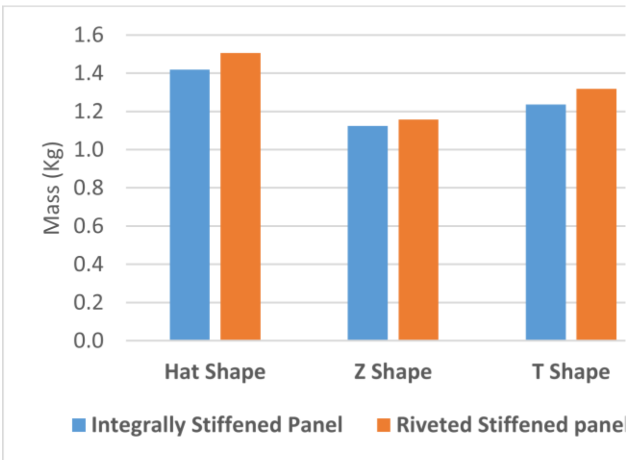

Fig. 8 Comparison of mass

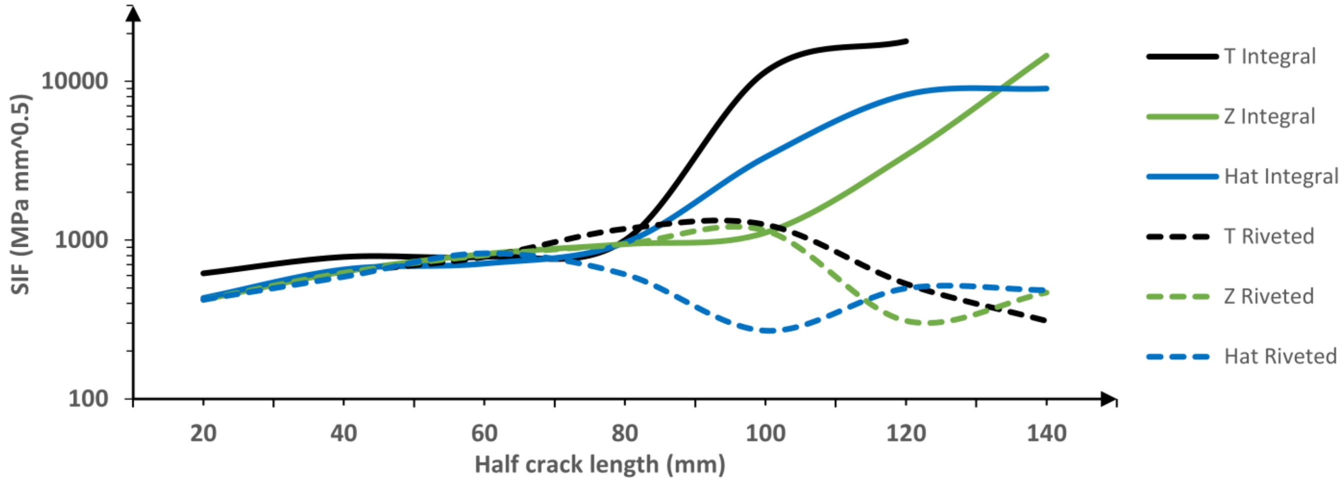

Fig. 9 Comparison of SIF

V. Damage Tolerance Analysis in AFGROW

The purpose of this analysis was to perform the damage tolerance analysis of the panels in AFGROW. AFGROW does not have a capability to model stiffened panels. However other than a built-in library of SIF solutions, there is a user defined beta table method which allows crack growth analysis of non-standard geometries such as stiffened panels. In this method beta factor is used to incorporate the geometrical features of the model. The beta factor is obtained from the SIF's calculated through FEA by using the equation $K_I = \beta\, \sigma\sqrt{\pi c}$ where K_I is the SIF, "σ" is the relevant applied stress, and "c" is crack length [9]. In this analysis the NASGROW crack growth model was used and AL 2024-T351 was selected from the material database of NASGROW. Normalized TWIST loading spectrum with the stress multiplication factor (SMF) of 100 MPa was used to simulate the real life loading conditions on the panels.

A. Individual Comparison of a Z, T and Hat shaped integrally stiffened panel and a Z, T and Hat shaped riveted stiffened panel

The damage tolerance analysis of a quarter model of both types of Z, T and Hat shaped stiffened panels was performed in AFGROW. The width of the model was 250 mm and the initial crack length was 20 mm. Initially the crack growth rate was equal in both of the panels but as the crack approached the stiffener, the crack growth rate was greater in integrally stiffened panel as shown in Fig. 10, Fig 11 and Fig. 12. This proves that riveted stiffened panel has better damage tolerance as compared to integrally stiffened panel.

B. Overall comparison of Z, T and Hat shaped integrally stiffened panels and a Z, T and Hat shaped riveted stiffened panels

The crack growth curve of all the models was obtained in AFGROW and plotted on a same graph (Fig. 13). From the crack growth curve it can be seen that hat shaped riveted stiffened panel has the maximum damage tolerance because it gives the maximum number of loading cycles for a given crack length. T shaped integrally stiffened panel has the greatest damage tolerance among the integrally stiffened panels therefore it can be concluded that T shaped integrally stiffened panel would be most appropriate for further analysis.

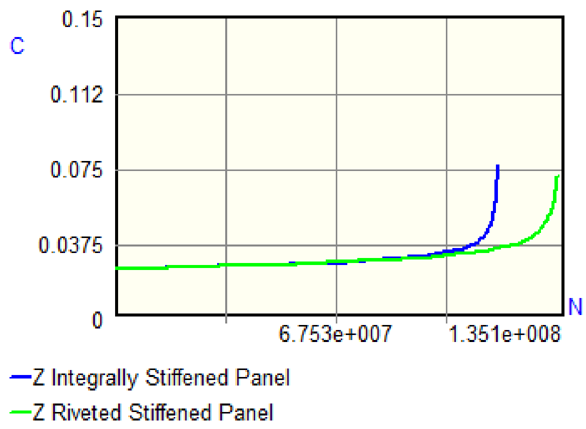

Fig. 10 Comparison of Crack growth curve for Z shaped panels

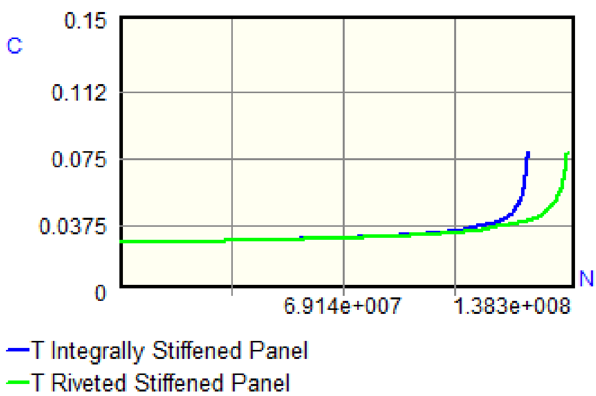

Fig. 11 Comparison of Crack growth curve for T shaped panels

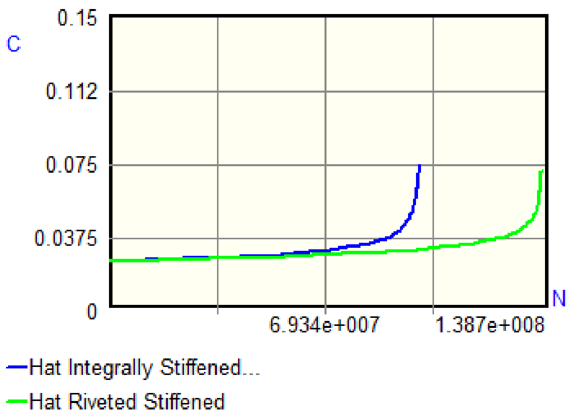

Fig. 12 Comparison of Crack growth curve for Hat shaped panels

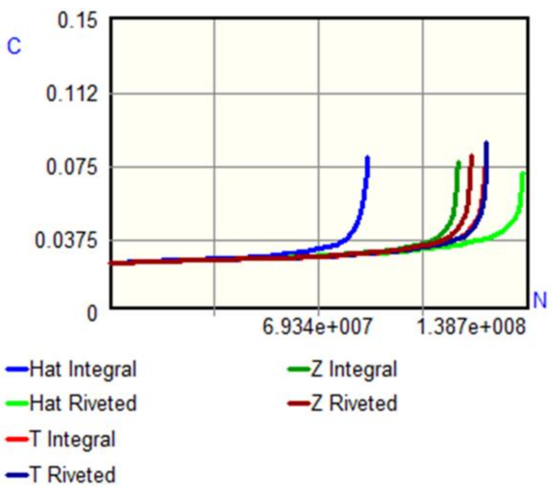

Fig. 13 Combined comparison of crack growth curve of Hat, T and Z shaped stiffened panels

VI. Conclusion

We have compared the maximum stress, mass and damage tolerance life of both integrally and riveted stiffened panels while considering different shapes of stringers and concluded that integrally stiffened panels are advantageous in terms of mass and static strength. However, the riveted stiffened panels are still superior in damage tolerance. The hat riveted stiffened panels have the greatest damage tolerance life. Therefore in order to replace hat riveted stiffened panels further improvement in T and Z shaped integrally stiffened panels should be undertaken to improve the damage tolerance of integrally stiffened panels.

VII. Refrences

[1] Murphy, A., et al., Modified stiffened panel analysis methods for laser beam and friction stir welded aircraft panels. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2006. 220(4): p. 267-278.

[2] Fossati, M., et al., Numerical modelling of crack growth profiles in integral skin-stringer panels. Engineering Fracture Mechanics, 2011. 78(7): p. 1341-1352.

[3] Singha, K.L., K. Keswanib, and M. Vaggarc, Crack growth simulation of stiffened fuselage panels using XFEM techniques. INDIAN JOURNAL OF ENGINEERING AND MATERIALS SCIENCES, 2014. 21(4): p. 418-428.

[4] Pettit, R., J. Wang, and C. Toh, Validated feasibility study of integrally stiffened metallic fuselage panels for reducing manufacturing costs. 2000: NASA.

[5] Heinz, A., et al., Recent development in aluminium alloys for aerospace applications. Materials Science and Engineering: A, 2000. 280(1): p. 102-107.

[6] Brot, A., et al. The damage-tolerance behaviour of integrally stiffened metallic structures. in Israel Annual Conference on Aerospace Sciences. 2008.

[7] Shi, Z., Predicting fatigue crack growth life in integral metallic skin-stringer panels. 2012.

[8] Adeel, M., Study on Damage Tolerance Behavior of Integrally Stiffened Panel and Conventional Stiffened Panel. World Academy of Science, Engineering and Technology, 2008. 45.

[9] Harter, J.A., AFGROW users guide and technical manual. 1999, DTIC Document.