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COMPOSITE MATERIAL PROPERTY DATABASE USING SMOOTH SPECIMENS TO GENERATE DESIGN ALLOWABLES WITH UNCERTAINTY ESTIMATION

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ABSTRACT

In developing composite material property database, three categories of data are needed. Category 1 consists of all raw test data with detailed information on specimen preparation, test machine description, specimen size and number per test, test loading history including temperature and humidity, etc., test configuration such as strain gage type and location, grip description, etc. Category 2 is the design allowable derived from information contained in Category 1 without making further experimental tests. Category 3 is the same design allowable for applications such that new experiments prescribed by user to obtain more reliable properties for the purpose on hand.

At present, most handbook-based composite material property databases contain incomplete information in Category 1 (raw data), where a user is given only the test average values of properties such as longitudinal, transverse, and shear moduli, major and out-of-plane Poisson's ratios, longitudinal tensile and compressive, transverse tensile and compressive, and shear strengths, inter-laminar shear strength, ply thickness, hygro-thermal expansion coefficients, specific gravity, fiber volume fraction, etc. The presentation in Category 1 ignores the inclusion of the entire test environment description necessary for a user to assess the uncertainty of the raw data. Furthermore, the design allowable listed in Category 2 is deterministically obtained from Category 1 and the user is given average design allowable without uncertainty estimation. In this paper, it is presented a case study where average design allowable failure envelopes of open hole specimens were obtained numerically for two different quasi-isotropic carbon fiber-epoxy laminates using the appropriate Category 1 data. Using the method of statistical design of experiments, it is then showed how the average design allowable can be supplemented with uncertainty estimates if the Category 1 database is complete. Application of this methodology to predicting reliability of composite structures is discussed.

I. INTRODUCTION

Lightweight engineering structures such as aircraft fuselage contain a number of openings and notches due to the presence of windows, doors, access points, bolt holes, etc. Stress concentrations developed around these notches and openings make them a potential source for failure initiation. Thus numerous studies have been conducted to investigate the strength of notched laminates including open holes and filled holes [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15].

In aerospace industry, open hole tests have been standardized as a method to generate design allowable [16,17,18,19]. However, standards for such open hole tests are only limited to uniaxial tension or compression loadings. This is primarily due to the fact that testing for biaxially loaded specimens is not only very difficult but also expensive. Thus often, data generated from the open hole tension and compression tests, designated as Category 3, are coupled with criteria such as maximum stress criterion to estimate the strength in biaxial loads. Such approach may produce either over-conservative or unsafe design [20]. Further, such allowable generated using notched specimens are very much specific to the layup definition and geometry and therefore cannot be generalized. It is then recommended the notched allowable be computed using data-set from smooth specimens, producing Category 2 data using Category 1 data. This not only eliminates the erroneous approach of using uniaxial data to empirically estimate biaxial data but also reduces the experimental costs involved in design and optimization phase by one order of magnitude [21].

In order to obtain Category 2 data from Category 1 data, computational methods such as finite element analysis can be used [20]. However, results obtained from such numerical computation heavily rely on the accuracy of data supplied for Category 1, which are among many, mechanical and hygro-thermal properties of the composite. Although the standard practice in measuring these Category 1 data consists of the testing of a number of coupons, the results are often reported as average values without any statistical variation information. The material properties reported in industrial datasheet as well as standard handbooks only consists of such average values.

During numerical simulation to generate Category 2 data, the reported average values for Category 1 data, without any statistical variation, are taken into consideration, which leads to numerical results lacking statistical uncertainties. Also, the effect of the statistical variation of any property on the final result was ignored. Even with a state of the art numerical prediction tool, the results might be different from those expected as they do not include the statistical variations unlike experimental observations. It is apparent that the completeness of Category 2 data generated from Category 1 data is significantly dependent upon the completeness of the supplied raw data for the smooth specimens. Thus there is a need for including such statistical variation in Category 1 data.

In this work, numerical computation for design allowable of smooth specimen from Category 1 ply strength data is coupled with a statistical tool in order to estimate the open hole strengths with their respective statistical parameters for a quasi-isotropic laminate for biaxial loading condition.

II. TOOL FOR STATISTICAL ANALYSIS (DATAPLOT)

The statistical analysis performed in this work was based on the software Dataplot from NIST (National Institute of Standards and Technology) [22,23,24]. Dataplot is a multiplatform software for scientific visualization, statistical analysis and non-linear modeling. The option for Design of Experiments (DEX) was used. It allows associating an experimental design to a virtual finite element method simulation including variation on the input parameters in order to perform an estimation within 95% confidence interval.

III. NUMERICAL EXAMPLE

An open hole notched plate was considered as reported in an experimental study [12]. A square plate of 32mm x 32mm size has a central circular opening with a diameter of 6.35 mm as shown in Figure 1. The laminate was made up of quasi-isotropic $[45/90/-45/0]_{4s}$ IM7/8552 composite, with overall thickness of 4mm. The mechanical properties of the material are as shown in Table 1 [12], which forms Category 1 data.

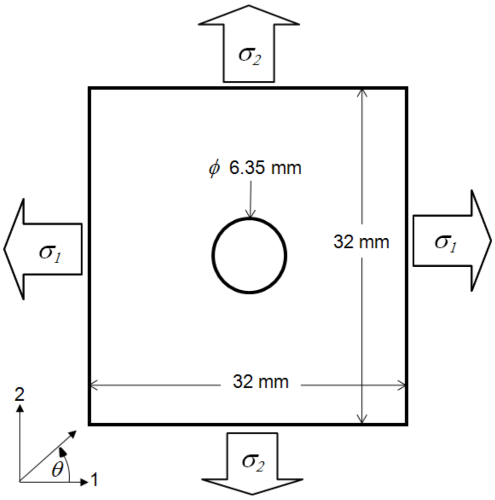

Figure 1. An open hole IM7/8552 plate

Table 1. Ply properties of IM7/8552 (Category 1) [12]

E_{11} GPa	E_{22} GPa	G_{12} GPa	ν_{12}	X/X' MPa	Y/Y' MPa	S MPa	Thickness mm
150	11	4.6	0.3	2,400/ 1,690	111/ 250	120	0.125

In Table 1, E_{11}, E_{22} and G_{12} are the longitudinal, transverse and shear modulus of elasticity, respectively; ν_{12} is the main Poisson's ratio; X, X', Y, Y', and S, are longitudinal tensile, longitudinal compressive, transverse tensile, transverse compressive and shear strengths, respectively.

It should be noted that Category 1 data reported in [12] are average values and do not have any statistical information (e.g., standard deviation, coefficient of variation, sample size, etc.). In order to consider the data for this work along with statistical variations based on the reference values in Table 1, four ply strengths were varied within feasible range as shown in Table 2. A total of 17 combinations, designated as Runs 1 though 17, were considered which would serve as input data for computational runs performed in this study. The first combination in Table 2 represents the average values.

Table 2. Ply properties variations for IM7/8552

	X MPa	**X'** MPa	**Y** MPa	**Y'** MPa
Run-1	2400	1690	110	250
Run-2	2064	1335	98	200
Run-3	2736	1335	98	200
Run-4	2064	2045	98	200
Run-5	2736	2045	98	200
Run-6	2064	1335	122	200
Run-7	2736	1335	122	200
Run-8	2064	2045	122	200
Run-9	2736	2045	122	200
Run-10	2064	1335	98	300
Run-11	2736	1335	98	300
Run-12	2064	2045	98	300
Run-13	2736	2045	98	300
Run-14	2064	1335	122	300
Run-15	2736	1335	122	300
Run-16	2064	2045	122	300
Run-17	2736	2045	122	300

It can be observed, in Table 2, that the variations were included only for tensile and compressive longitudinal strengths (X and X') and for tensile and compressive transverse strengths (Y and Y'). The coefficient of variations included were ±14% for X, ±21% for X', ±11% for Y, ±20% for Y', obtained using arbitrary two standard variations (2σ) for the average data from reference [12]. Such arbitrary variation was chosen primarily to observe the effect of such variation on the final result from the simulation, the result being the ultimate strengths of the specimen. Although in this work statistical variations considered are limited to these four ply strengths, the same should be considered for other properties in Table 1 for data completeness.

With inputs from Table 2, numerical analysis was performed to extract failure envelopes for the open hole specimen under inplane (σ_1,σ_2) biaxial loading conditions. For this, finite element method (FEM) based tool MicMac/FEA was chosen. The code interfaces with ABAQUS Student Edition to perform failure analysis of the given specimen at various biaxial loading combinations, plotting as result a failure envelope for the given specimen. The FEM model was created with conventional shell elements of quadrilateral S4R type. Since delamination was not observed in the experimental study [12] for the considered plate thickness, no delamination was simulated. A structured meshing scheme was implemented with 512 elements and 544 nodes as shown in Figure 2. A simultaneous degradation scheme was chosen to compute the ultimate strength of the specimen. In this scheme, once a failure initiation was noticed as per Tsai-Wu criterion, elastic properties of the whole laminate are degraded to obtain the ultimate ply failure strength. This method was chosen for demonstration purposes of statistical analysis due to its computational efficiency, although results obtained generally yields to relatively conservative predictions as compared to more accurate methods such as progressive damage models.

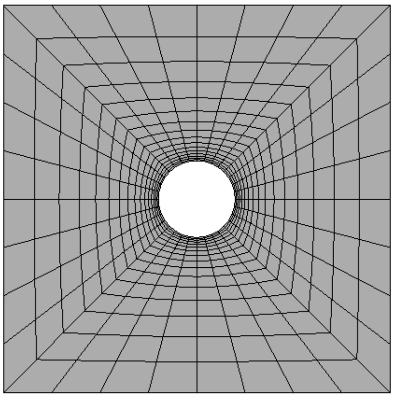

Figure 2. FEM mesh

IV. RESULTS AND DISCUSSION

A total of 17 failure envelopes were obtained for the open hole specimen. Each set corresponds to the input data (Runs-1 to 17) as reported in each row of Table 2. In Figure 3, a failure envelope obtained using average ply strengths (Run-1) is plotted along with the data obtained from entire combinations considered (Runs-2 to 17) in Table 2. It is evident that the allowable generated using average values do not address the possibility of the data scatter as would be covered by inclusion of statistical variation in the input strengths.

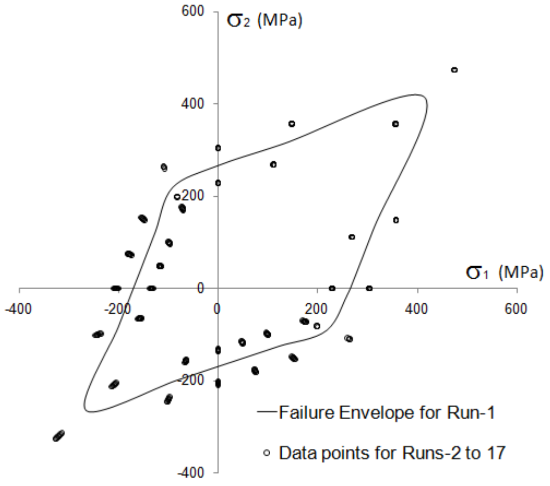

Figure 3. Failure envelope for the open hole specimen

Similarly, Figure 4 represents inner and outer limits for possible failure plot data points with all the statistical variation considered for the input ply level strength parameters (Runs 1-17).

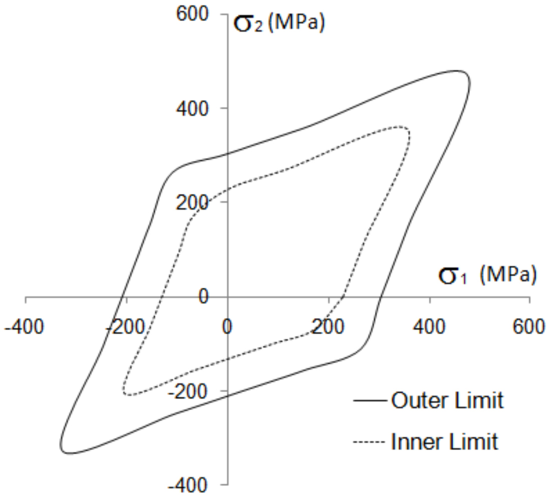

Figure 4. Limits for possible failure plot data points with all the statistical variation considered (Runs1-17)

In Table 3, biaxial strengths (σ_{1ULT}, σ_{2ULT}) of the specimen with properties considered in Run-1 (average values), Run-5 and Run-16 are given for varying load ratio. These given values are taken from the corresponding locus of the failure envelopes. It is observed that the computed biaxial strength with statistical variation in consideration can vary up to 22% of that of the strength obtained from average value only (Run-1).

Table 3. Computed biaxial strengths for representative Runs

Load ratio σ_1:σ_2	(σ_{1ULT}, σ_{2ULT}) MPa		
	Run-1	**Run-5**	**Run-16**
1:0	(266,0)	(304,0)	(228,0)
1:1	(415,415)	(474,474)	(356,356)
0:1	(0,266)	(0,304)	(0,228)
-1:1	(-125,125)	(-150,150)	(-152,152)
-1:0	(-170,0)	(-204,0)	(-207,0)
-1:-1	(-265,-265)	(-318,-318)	(-323,-323)
0:-1	(0,-170)	(0,-204)	(0,-207)
1:-1	(125,-125)	(150,-150)	(152,-152)

The statistical procedure adopted was to associate each experimental design to its respective finite element simulation in order to predict the selected strengths within a 95% confidence interval. Using the finite element analysis results, it was possible to estimate the statistical strength parameters for all the eight load cases studied. Therefore, Figures 5 to 10 graphically depict these parameters in a normal distribution. Here, Figure 5 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of 1:0 (unidirectional tensile). Figure 6 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of 1:1 (first quadrant in σ_1-σ_2 domain). Figure 7 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of -1:1 (second quadrant in σ_1-σ_2 domain). Figure 8 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of -1:0 (unidirectional compressive). Figure 9 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of -1:-1 (third quadrant in σ_1-σ_2 domain). Similarly, Figure 10 presents the strength estimated with respective statistical parameters for load ratio σ_1:σ_2 of 1:-1 (fourth quadrant in σ_1-σ_2 domain).

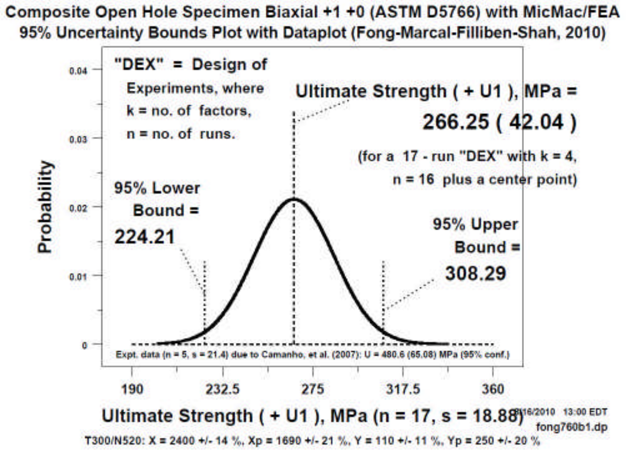

Figure 5. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of 1:0

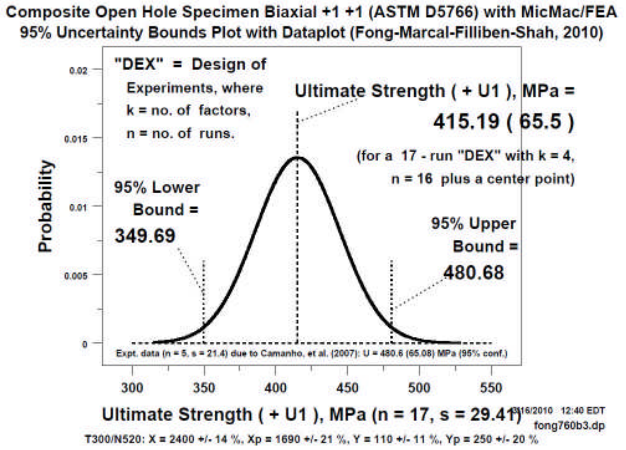

Figure 6. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of 1:1

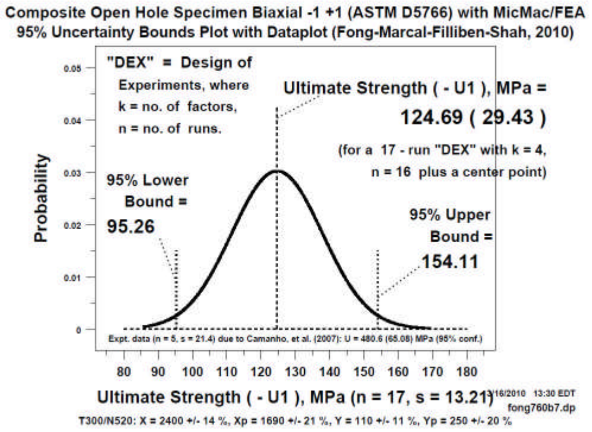

Figure 7. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of -1:1

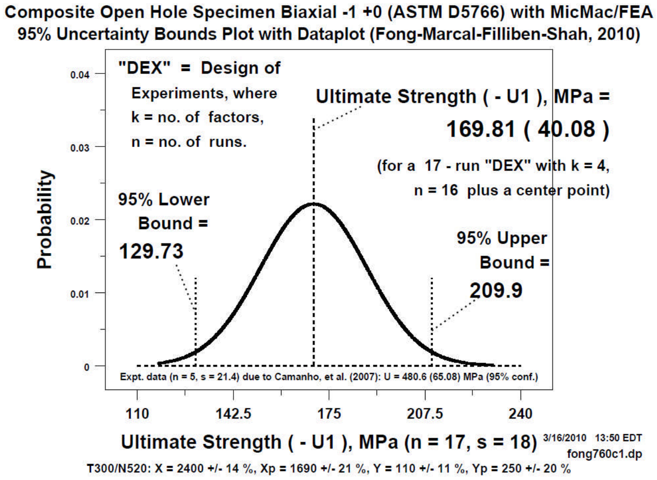

Figure 8. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of -1:0

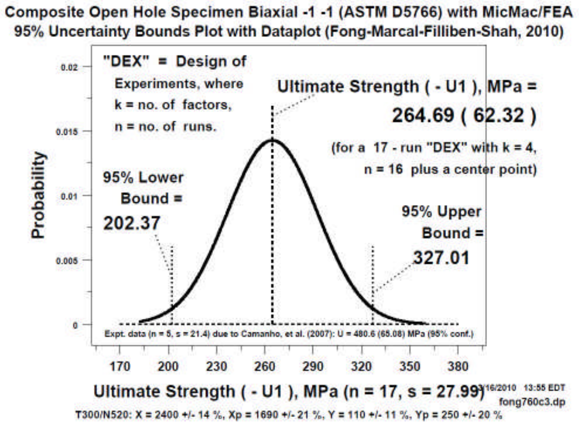

Figure 9. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of -1:-1

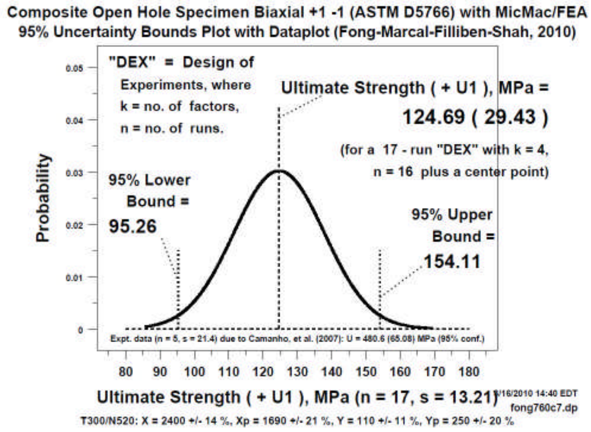

Figure 10. Estimated open hole laminate statistical strength parameters for load ratio $\sigma_1:\sigma_2$ of 1:-1

Table 4 shows a summary of the main estimated statistical strength parameters for all load ratio cases, which are mean, standard deviation, coefficient of variations and 95% bounds. The coefficient of variations is given by the standard deviation divided by the mean. It can be observed that the coefficient of variations for the three first load ratio cases $\sigma_1:\sigma_2$ of 1:0, 1:1, and 0:1 presented the same value of 0.071. On the other hand, the coefficient of variations for the remaining five load ratio cases (-1:1, -1:0, -1:-1, 0:-1, and 1:-1) also presented the same value, 0.106, however different from the previous three load ratio cases. This occurs because the open hole biaxial strengths for the first three load ratio cases were controlled by the ply tensile strength, which had lower variation, while the strengths for the remaining five load ratio cases were controlled by the ply compressive strength, which had higher variation (Table 2).

Table 4. Estimated open hole laminate statistical strength parameters based on the finite element simulations

Load ratio $\sigma_1:\sigma_2$	**Estimated open hole laminate strength MPa**			
	Mean	**Standard Deviation**	**Coefficient of Variations**	**95% Bounds**
1:0	266.25	18.88	0.071	42.04
1:1	415.19	29.41	0.071	65.50
0:1	266.25	18.88	0.071	42.04
-1:1	-124.69	13.21	0.106	29.43
-1:0	-169.71	18.00	0.106	40.08
-1:-1	-264.69	27.99	0.106	62.32
0:-1	-169.71	18.00	0.106	40.08
1:-1	124.69	13.21	0.106	29.43

V. CONCLUSION

The results obtained in this study establish the importance of inclusion of statistical variation in Category 1. Ignoring the statistical variation for smooth specimen data readily affects the completeness of design allowable generated as Category 2 data. Deterministic result obtained from the traditional average-value-type of calculations is inadequate as a basis for reliability analysis of composite structures. Our approach in this paper is to introduce a methodology whereby all database values could now have experimental and numerically modeled values with standard deviations. This approach will allow engineers to use statistical tests [25,26] such as *t*-test, *chi-square*-test, and *F*-test, to validate the numerically modeled with experimental data.

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VII. DISCLAIMER

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