PROGRESSIVE FAILURE ANALYSIS OF COMPOSITE OVERWRAPPED PRESSURE VESSEL

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Abstract

Stress and progressive failure analysis (First Ply Failure to Last Ply Failure) of a composite overwrapped pressure vessel (COPV) with an aluminum liner using the finite element method (FEM) in general and commercial finite element analysis (FEA) software ANSYS in particular is presented in this paper. Ply failure prediction is based on failure criteria implemented in ANSYS software. The first-ply failure (FPF) does not necessarily imply the total failure of a laminate. After FPF, the laminate stiffness is reduced consistent with identified ply failure mode. The strength of the composite laminate is evaluated again to see if it could carry additional load. This ply-by-ply analysis progresses, until the ultimate strength is reached. In the present study the methodology is validated using benchmarks and applied to a filament wound fibre reinforced plastic composite pressure vessel with an aluminum liner. Significant results are presented and critically assessed. Directions for further work in this field are identified.

***Keywords**: Progressive Failure Analysis, FEM, COPV, FPF, Stiffness Degradation*

Introduction

Pressurized systems are required in many spacecraft in order to operate fluid management and propulsion systems. High performance COPVs are being utilized in the aerospace and automotive industries for many years, providing an inherently safe, light weight and cost effective storage source for pressurized fluids. In a typical COPV design, a thin metallic liner is overwrapped with a fibre reinforced polymer matrix composite laminates. Reliable design of such pressure vessels demands development and validation of finite element models for stress analysis and strength prediction. COPV liners are generally made of ductile materials, such as soft aluminium, with only minimal load-sharing capabilities. Recent projects have begun using plastic-lined COPVs to minimize weight. The fibre is applied as a ribbon of multiple fibres that passes through a bath for resin application. This ribbon of fibre and resin is wound on the liner as one would wind a ball of string. The pressure vessel liner and the dispensing head for the fibres ribbon move in relation to one another in such a way as to wrap the fibre on the liner in a desired pattern. Fibre winding is applied in both a longitudinal (helical) and a circumferential (hoop) wrap. Circumferential (hoop) wrap is not continuous with the end dome winding. This winding process consists of multiple critical steps, such as resin content, fibre configuration, winding tension, and the pattern of the wrap in relation to the axis of the liner. The resin is then allowed to cure (dry and harden) at an elevated temperature. The chosen commercial FEA software namely ANSYS has the capabilities to predict ply by ply stresses in the material coordinates for the laminate within every finite element in the mesh. The software displays contour plots of failure index for each ply based on the chosen failure criteria.

Three dimensional finite element analysis of damage accumulation in composite laminates is presented by Lee [1]. The modes of failure determined included fiber failures, matrix failures and delaminations. Vijayakumar et al. [2, 3] presented an improved finite element model for the stress analysis of a filament wound fiber reinforced plastic pressure vessel with an elliptical cutout including layer wise stresses. However strength prediction was not attempted. Reddy and Pandey [4] have presented a finite element analysis, based on the first-order shear deformation theory of laminated composite plates subjected to in-plane and/or transverse loads. However laminate strength prediction was limited to FPF. Ray and Satsangi [5] have applied the FEM to predict the FPF loads of laminated composites stiffened panels. Pal and Ray [6] have presented a progressive failure analysis for angle ply laminated composite plates under transverse static loading using first-order shear deformation theory with shear correction factor. Pandey and Reddy [7] have extended their earlier work on first-ply failure of laminated composites to include a progressive failure analysis procedure. Reddy and Reddy [8] have presented a three dimensional finite element model and progressive failure algorithm for composite laminates under axial tension. A number of stiffness degradation models [9,10,11] have been proposed for studying damage in composite laminates. Chang and Chang [10] used a phenomenological failure criterion to study stiffness degradation of laminated composite structures.

This review of related research shows that the problem of stress analysis and burst pressure prediction of a composite overwrapped pressure vessel with a metallic liner has not been addressed. This in fact is the motivation for the pilot study reported in this paper.

Finite Element Modeling

Finite element modeling is defined here as the analyst's choice of material models, finite elements, meshes, constraint equations, analysis procedures, governing matrix equations and their solution methods, specific pre and post processing options in the chosen commercial FEA software for the intended analysis of identified component or structure. The focus of this work is on the use of ANSYS software for stress and progressive failure analysis of a filament wound fibre reinforced plastic composite pressure vessel with integral end domes and a metallic liner shown in Fig.1. This COPV with 1mm thick Aluminium liner is a four-piece construction that consists of two heads, a cylinder, and an outlet tube. The inner diameter of the cylindrical portion is 398mm, the length of cylindrical portion is 160mm and the overall length of COPV is 370mm. T300/5208 graphite/epoxy material is used for lay-up. Laminate Stacking Sequence (LSS) for the two models considered for the analysis are LSS I: ($\pm45/\pm60/\pm45/90_2$), and LSS II: ($\pm45/\pm60/\pm45/90_2/\pm45$) in circular cylindrical region, and the common Laminate Stacking Sequence (LSS) over dome region is ($\pm45//\pm60/\pm45$). Fibre direction 90° is along hoop direction. Each layer is of 0.5mm thickness. The material properties [11] of Graphite/epoxy are given in Table-1.

Table-1 : Material Properties

Properties	Units	Graphite/ Epoxy
Young's Modulus in fibre direction E_1	GPa	181
Young's Modulus in matrix direction E_2	GPa	10.30
In plane shear Modulus G_{12}	GPa	7.17
Poisson's ratio ν_{12}	-	0.28
Tensile strength in fibre direction X_t	MPa	1500
Compressive strength in fibre direction X_c	MPa	1500
Tensile strength in matrix direction Y_t	MPa	40
Compressive strength in matrix direction Y_c	MPa	246
In plane shear strength S	MPa	68

The Young's modulus of Aluminium is 70000 MPa and the Poisson's ratio 0.3. The analysis is carried out for an internal pressure of 1MPa. A typical finite element model of COPV is given in Fig.2. Nonlinear analysis is carried out in predicting the failure of composite structures to account for combined geometric and material nonlinearities. To run a progressive failure analysis the status of each ply in a laminate is periodically checked against the chosen failure index. When the failure index indicates that a ply has failed, it is numerically simple to replace the intact ply with failed ply, and then recalculate the laminate stiffness matrices. Progressive failure analysis involves recalculation of element stiffness and subsequent recalculation of the assembled stiffness matrix. Significant results obtained from parametric studies are presented and critically assessed in the next section.

Herein, a simple hypothetical stiffness reduction model is proposed to study the strength of damaged composite structure using the failure criteria. The applied load should be below the specified level to initiate damage to ensure reliability and safety in design, which necessitates the first-ply failure analysis. After failure at one point, the load continues to be carried by the remaining fibers and matrix of the lamina. Failure of a portion of one lamina is compensated for by an increase in the load carried by adjacent laminae. If failure occurs at the initial load, the analysis can be restarted at a lower initial load. If no failure occurs at the initial load, then the FPF load is calculated. The appropriate failure criterion is chosen from those described previously. In order to use any failure criteria more efficiently, the strength ratio (SR) is defined as the strength over the applied stress. The concept of strength ratio is applicable to any failure theory. If SR > 1, then the lamina is safe and the applied stress can be increased by a factor of SR. If SR < 1, the lamina is unsafe and the applied stress needs to be reduced by a factor of SR. A value of SR = 1 implies the failure load. The initial load is multiplied by this factor to give the first ply failure load. Since the analysis is elastic until failure, it is possible to determine the failure load by simply scaling up the stresses until the SR (the value found by evaluating the failure criterion) is equal to 1.

The strain at FPF can be easily calculated from the FPF strength because the material linear elastic until FPF. After FPF, the material behavior is nonlinear. In the present implementation of the material degradation model, the material properties which are degraded depend upon the failed ply. When fiber and/or matrix failure or shear failure is detected, fully discount the ply by moduli E_1, E_2, shear modulus G_{12} and the Poisson's ratio v_{12} set equal to reduce to a fraction of the original values. Fractions of the original stiffness values avoid singularities in stiffness and compliance matrices. Target stiffness was a dominant parameter and controlled the mode of fracture. The updated layer wise material moduli are then used to modify the element stiffness matrices of the damaged composite structure. The degradation of the stiffness and strength properties of each failed lamina depends on the philosophy followed by the user. At the final stage, the contribution of fiber breakage becomes important and the breakage of fibers may finally lead to the total collapse of the structure. Last ply failure (LPF) occurs after the structure has degraded to the point where it is no longer capable of carrying additional load. The consequence of individual failure modes is not of great interest for FPF, but will be of great importance in determining LPF.

Results Presentation and Discussion

The computed stresses and strength ratios are presented in Table-2 and Table-3. The FPF pressure is given by

$$FPF = SR \times p_{ref}$$

Table-2 presents stresses σ_1, σ_2 and τ_{12} of each ply and the von- Mises stress of metallic liner for LSS-I. Strength ratios are obtained by maximum stress, maximum strain, Hoffman and Tsai-Wu failure criteria are also included. Similarly Table-3 presents the stresses of each ply, the von Mises stress of metallic liner and strength ratios obtained at the top, middle and bottom surfaces of each ply using maximum stress, maximum strain, Hoffman and Tsai-Wu failure criteria are included. The effect of failure criteria on prediction of FPF load is evident from Table-4. It is observed that, by the addition layers (±45°) in LSS II, FPF loads are increased as per an assumed failure criteria. Strength ratios are estimated for the remaining plies until the LPF. Based on Tsai-Wu failure criterion the strength ratio of ply #2 (45°) for LSS I gives the LPF load = 10.7485 MPa. Similarly for LSS II the LPF load occurs in Ply #2 (45°) and its magnitude is 13.2642 MPa.

A critical assessment of the analysis with results is in order. The behavior of this complex shell structure upto final failure is not addressed in this preliminary study. However the proposed finite element model and the chosen FEA software has the desired capability. Further refinement of the FE mesh may become necessary to assure convergence. The validity of the converged solution needs to be verified. This demands a comprehensive experimental investigation. Further research is needed to arrive at a satisfactory combination of ply failure criteria, laminate stiffness degradation, updating the geometry and tracking the non-linear behavior upto burst. Development of required hydro test facilities and instrumentation is highly demanding. These are addressed in research program currently in progress. From the designers perspective optimization studies that can handle multiple objectives of weight, cost and performance are essential.

Conclusions

Design of composite overwrapped pressure vessels for specific applications, demands FE modelling for stress and progressive failure analysis of laminated composite shell structures. Validation of FE models using benchmarks, a standard set of test problems with known target solutions is a pre-requisite. Experimental investigations are mandatory to verify the accuracy, repeatability and reliability of predicted behaviour. Optimization studies are indispensible to arrive at a competitive design especially for aerospace applications. A review and assessment of the state of the art in this field is in progress to formulate research and development projects.

Table-2 : In-plane Stresses of Each Ply with Strength Ratios and the Von-Mises Stress of Metallic Liner (LSS I)

Ply #	Position	Lamina Stresses (MPa)			Strength Ratios				Von-Mises Stress (MPa)
		σ_1	σ_2	τ_{12}	Max. Stress	Max. Strain	Hoffman	Tsai-Wu	
1 (Liner)									78.29
2 (45°) 0.5 mm	Top	92.436	6.593	8.659	6.0668567	7.077291	9.97513	4.440872	
	Middle	91.393	6.504	8.954	6.2046286	7.005057	9.916874	4.443129	
	Bottom	90.35	6.445	9.316	5.8568583	6.934283	9.793552	4.445156	
3 (-45°)	Top	94.935	6.831	9.422	5.8582308	7.216725	9.545609	4.415167	
	Middle	93.932	6.696	9.508	5.9737156	7.150978	9.614464	4.430248	
	Bottom	92.929	6.590	9.607	6.0716454	7.077291	9.64649	4.440714	
4 (60°)	Top	87.39	8.93	6.722	4.4792632	4.763333	7.778201	3.873657	
	Middle	82.69	8.88	6.97	4.5020304	4.775982	7.546471	3.884913	
	Bottom	78.00	8.84	7.265	4.5250506	4.788675	7.312858	3.896053	
5 (-60°)	Top	91.688	9.033	7.869	4.4280508	4.728288	7.692978	3.848567	
	Middle	87.657	8.986	7.938	4.4513093	4.742303	7.520474	3.860423	
	Bottom	83.656	8.939	8.007	4.4748135	4.756400	7.358073	3.872157	
6 (-45°)	Top	107.125	8.02	8.938	4.9877799	6.284999	9.164302	4.320345	
	Middle	104.29	7.781	9.016	5.1385084	6.490977	9.205292	4.336645	
	Bottom	101.454	7.549	9.095	5.2986308	6.710958	9.249003	4.352766	
7 (45°)	Top	121.334	8.145	6.498	4.9108195	6.363063	10.86259	4.293541	
	Middle	117.542	7.94	6.636	5.5098543	6.526605	10.74879	4.30962	
	Bottom	113.954	7.734	6.775	5.1718876	6.698776	10.66884	4.325521	
8 (90°)	Top	37.043	11.544	0.061	3.4649074	3.421622	4.713	3.456106	
	Middle	33.205	11.518	0.519	3.4727045	3.420311	4.627018	3.466781	
	Bottom	30.866	11.493	0.425	3.4805247	3.419002	4.581211	3.477426	
9 (90°)	To	46.576	11.596	0.080	3.4494653	3.424235	4.944011	3.434632	
	Middle	41.809	11.570	0.706	3.4578146	3.422934	4.823188	3.445389	
	Bottom	37.043	11.544	0.061	3.4640432	3.421271	4.713	3.456106	

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Table-3 : In-plane Stresses of Each Ply with Strength Ratios and the Von-Mises Stress of Metallic Liner (LSS II)

Ply #	Position	Lamina Stresses (MPa)			Strength Ratios				Von Mises Stress (MPa)
		σ_1	σ_2	τ_{12}	Max. Stress	Max. Strain	Hoffman	Tsai-Wu	
1 (Liner)									64.79
2(45°)	Top	83.933	5.818	8.297	6.8749312	8.196116	10.70493	5.73489857	
	Middle	82.938	5.667	8.577	7.0585577	7.928516	10.76489	5.58731010	
	Bottom	81.943	5.597	8.857	7.1460728	7.677778	10.69601	5.73687260	
3(-45°)	Top	85.569	6.247	7.773	6.4028684	8.177417	10.36208	5.65153750	
	Middle	83.405	6.026	7.845	6.6379024	8.437109	10.53238	5.65559677	
	Bottom	81.431	5.917	7.932	6.7596798	8.196116	10.54813	5.65914942	
4(60°)	Top	102.673	6.836	6.476	5.8516147	6.144959	11.1142	4.98939753	
	Middle	93.888	6.789	6.702	5.8918839	6.190685	10.48408	5.00087515	
	Bottom	85.159	6.764	6.959	5.9138004	6.219795	9.885749	5.01082337	
5(-60°)	Top	115.611	7.13	6.488	5.6100981	6.052096	11.71796	4.92416781	
	Middle	107.454	6.912	6.547	5.7874389	6.095665	11.34441	4.95653122	
	Bottom	99.296	6.89	6.607	5.8055152	6.091395	10.74607	4.97594132	
6(-45°)	Top	107.502	8.151	7.346	4.9073010	6.127225	9.545601	4.78075459	
	Middle	102.696	7.803	7.417	5.1265225	6.416384	9.584539	5.09364669	
	Bottom	97.89	7.454	7.488	5.3662175	5.934858	9.652273	5.42272882	
7(45°)	Top	127.28	8.292	6.761	4.8236707	6.120550	11.1185	4.36532534	
	Middle	122.054	7.97	6.383	5.0190976	6.382313	11.17968	4.63252495	
	Bottom	116.828	7.664	6.527	5.2195335	6.667466	11.0738	4.91963771	
8(90°)	Top	28.826	9.301	0.163	4.3006313	4.231586	5.665194	4.32466094	
	Middle	26.957	9.24	0.135	4.3289855	4.242789	5.649126	4.35361829	
	Bottom	26.272	9.179	0.107	4.3578301	4.254033	5.668315	4.38269711	
9(90°)	Top	32.565	9.423	0.220	4.2451488	4.209480	5.699492	4.26719466	
	Middle	30.695	9.362	0.191	4.2727191	4.220495	5.68197	4.29586480	
	Bottom	28.826	9.301	0.163	4.3006313	4.231586	5.665194	4.32466094	
10(-45°)	Top	84.661	5.998	6.775	6.6687562	8.603704	11.0491	5.17081797	
	Middle	83.241	5.903	6.846	6.7766287	8.740723	11.0888	5.21240552	
	Bottom	81.821	5.807	6.918	6.8880485	8.882099	11.13281	5.25392205	
11(45°)	Top	86.008	6.251	0.749	6.3988942	8.195646	11.99504	5.06367572	
	Middle	84.7	6.151	0.820	6.5030076	8.330903	12.08135	5.10683498	
	Bottom	83.393	6.051	0.892	6.6105213	8.470628	12.17204	5.15002008	

Table-4 : Ply Failure Loads

Failure Criteria	FPF (MPa) (LSS I)	FPF (MPa) (LSS II)
Max. Stress	3.449	4.245
Max. Strain	3.419	4.209
Hoffman	4.627	5.649
Tsai-Wu	3.436	4.295

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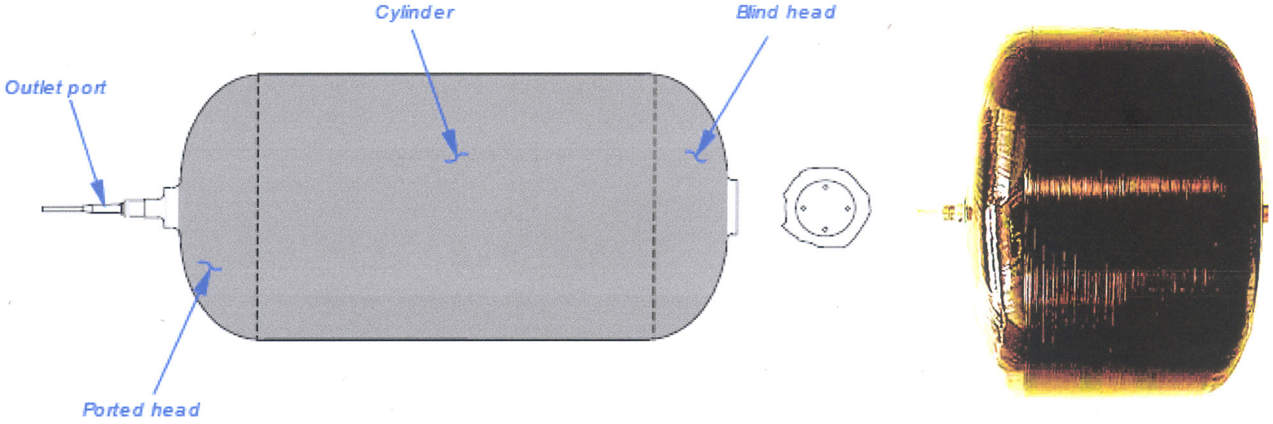
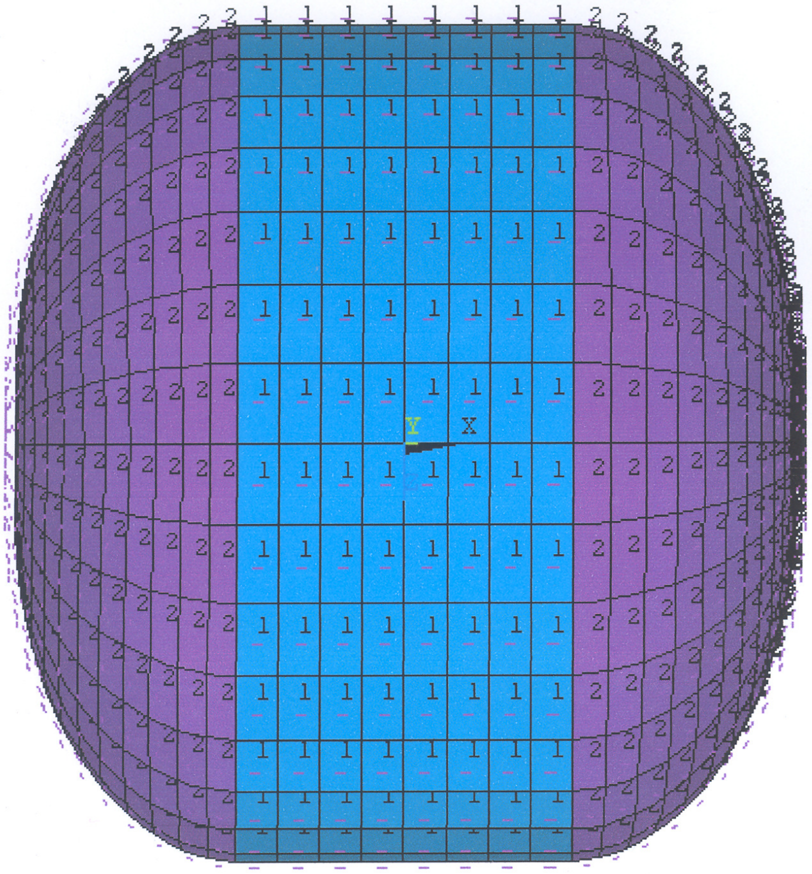


Fig.1 Composite Overwrapped Pressure Vessel (COPV)



Cylindrical portion **(Property Set #1):**

LSS I: $(\pm45/\pm60/\pm45/90_2)$; **LSS II:** $(\pm45/\pm60/\pm45/90_2/\pm45)$

Dome portion **(Property Set #2):**

LSS: $(\pm45/\pm60/\pm45)$

Fig.2 Typical Finite Element Model