THE INFLUENCE OF MULTIPLE NESTED LAYER WAVINESS ON COMPRESSION STRENGTH OF CARBON FIBER COMPOSITE MATERIALS

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ABSTRACT:

As advanced composite materials having superior physical and mechanical properties are being developed, optimization of their production process is eagerly being sought. One of the most common defect in production of structural composites is layer waviness. Layer waviness is more pronounced in thick section flat and cylindrical laminates that are extensively used in missile casings. Submersibles and space platforms. Layer waviness undulates the entire layer of a multidirectional laminate in through-the-thickness direction leading to gross deterioration of its compression strength.

This research investigates the influence of multiple layer waviness in a double nest formation on the compression strength of a composite laminate. Different wave fractions of wavy 0° layer were fabricated in IM/8551-7 carbon-epoxy composite laminate on a steel mold using single step fabrication procedure. The laminate was cured on a heated press according to specific curing cycle. Static compression testing was performed using NASA short block compression fixture on an MTS servo hydraulic machine. The purpose of these tests was to determine the effects of multiple layer wave regions on the compression strength of composite laminate. The experimental and analytical results revealed that up to about 35% fraction of wavy 0° layers. The reduction in compression strength of composite laminate was constant after fraction of wavy 0° layers exceeded 35%. This analysis indicated that the percentage of 0° wavy layer may be used to estimate the reduction in compression strength of a composite laminate under restricted conditions.

INTRODUCTION:

The poor compressive strength of carbon-epoxy composite materials represents its ‘Achilles Heels’. This seriously limits the design performance of its structural components. The compression strength of unidirectional composites depends on many factors including the waviness of the reinforcing fibers. Under compressive loading, layer waviness in a composite laminate produces Eulerian bending which causes a significant loss of compacting strength. The generation of layer waviness is often attributed to poor method of compacting the laminate during curing. This degree of waviness may be reduced by altering the manufacturing process. Although the effects of single nest layer waviness on compression strength of laminates are well documented, the influence of double nested layer waviness on compression strength have hardly been addressed.

Research into the effects of layer waviness on structural performance began largely in response to the industrial requirements. The first evidence of significant degradation in compression strength as a result of layer waviness was reported by Garala [1]. He subjected several carbon-epoxy cylinders to external hydro static pressure but they failed well below the design pressure believed to be due to layer waviness. This initiated several research activities that were presented for several years at

‘Thick Composites in Compression Workshops’ held at Oak Ridge National Laboratory during 1987-90. Gascoigne and Abdallah used moiré interferometery to show that layer waviness in externally pressurized cylinders produced large interlaminate strains and substantial reduction in its compressional strength [2]. Research at Virginia Tech by Adams and Hyer showed the application of finite element analysis for predicting degradation due to idealized forms of layer waviness [3]. Bogetti, Gillespie and Lamontia developed a model based on laminated plate theory (LPT) for idealized form of layer waviness at University of Delaware, [4] U.K. The other first perceived this phenomena whilst working on a real problem area of British Aerospace regarding machining in thick composite panels at Salford University UK, 1988-91, discussed the concept in the 18th International Summer College at Nathiagalli, Pakistan, 1993 [5], presented the phenomena in a composite workshop at International Center for Science and High Technology, Trieste, Italy, 1994, and carried out proposed research in collaboration with NASA at Iowa State University of Science and Technology, USA, 1995-97.

THE RESEARCH OBJECTIVE:

The objective of this research program is to correlate the fraction of wavy 0° layer in a double nest formation with the reduction in the compression strength of a composite laminate. This research also aims to comprehend the fundamentals if deformation mechanism of wavy layers in composite laminate under compressive loading. This research will lead to further understanding of layer waviness effects, which will have direct implications on establishment of its accept/reject criteria in composite structures.

COMPOSITE FABRICATION:

Different formations and volume fractions of double nested wavy 0° layer were produced in IM7/8551-7A Carbon-Epoxy prepreg having cross supply orientation in a single step fabrication procedure as indicated in Table-1. Double nested implies two identical formations of wavy 0° layers that are separated by straight 0° layer e.g. 3 wavy 0°, 1 straight 0° and 3 wavy 0° layers and are also fold on top/bottom by 90° layers. Each 0° and 90° layer consisted of two plies. Production of waviness into cross ply laminates was accomplished by removing two thin strips of prepreg materials from the adjacent 90° plies.

Table-I: Lay-up configuration in the laminate having Double Nested Wave (DNW) i.e. [2-3W-4-3W-3] signified by [2: straight, 3: wavy, 4: straight, 3: wavy and 2: straight 0°] layers that are separated and folded on top/bottom by 0° layers.

Panel N0.	Lay-up Configuration	0° Layers	Wavy 0° Layers	Wave Fraction, f_w
DNW-1	3-1W-6-1W-3	12	2	0.1242857
DNW-2	2-1W-8-1W-2	12	2	0.1242857
DNW-3	2-1W-4-1W-2	8	2	0.2
DNW-4	2-2W-4-2W-2	8	4	0.33333
DNW-5	2-1W-4-1W-2	8	6	0.428571
DNW-6	1-3W-5-3W-1	7	6	0.428571
DNW-7	2-3W-2-3W-2	6	6	0.5
DNW-8	1-3W-2-3W-1	6	4	0.5
DNW-9	1-3W-2-3W-1	4	6	0.6

Once strip was rolled by hand into a cylinder and placed above the 0° layer for production of central wave trough. The other strip was divided in half, rolled into two smaller cylinders and placed below the 0° layer where adjacent wave crest was desire as shown in fig-1. The way 0° layer in actual specimen is shown in fig-2. In case of multiple layer waviness, the strips are rolled in a similar manner but placed above and below the group/multiple of desired 0° and 90° wavy layers. The remaining 0° and 90° plies were placed on each side of the wavy layer assembly to obtain the desired final stacking sequence. The double nests of wavy layers were obtained by stacking the two nests (each composed of a single or in phase multiple wavy 0°) on top of each and separated by 0. The prepregs were cut to 152 mm squares and placed in corresponding steel well and plunger mould for curing in a heated press. The cure cycle consisted of applying 340 kPa of pressure while ramming the temperature from room temperature to 120°C in one half hour. After one hour at 120°C, the pressure was increased to 550 kPa and the temperature was rammed to 180°C over one half and held for two hours. The laminate was cooled and removed from the mold and cut by diamond disc saw to the desired tests specifications for compression tests.

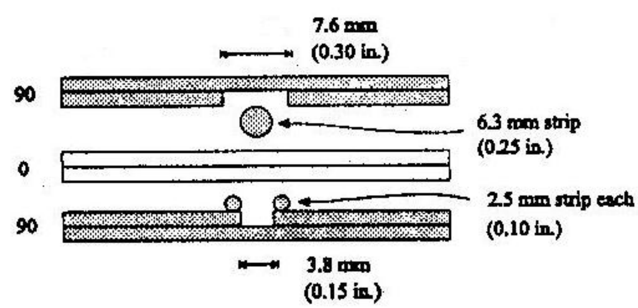

Fig.-1: Fabrication of a single wave in a laminate

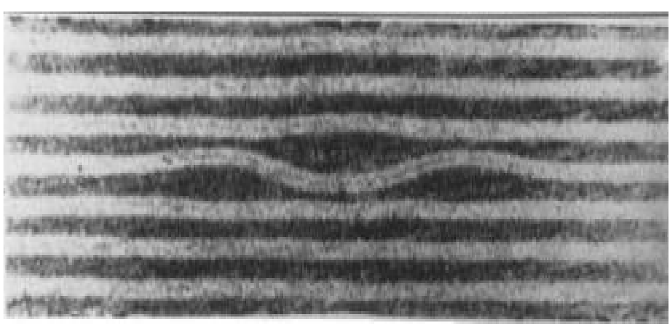

Fig.-2: Single layer wave in test specimen

COMPRESSION TESTING:

The specimen was clamped in NASA Short Block Compression Test Fixture, WTF-NC. The fixture was placed on a ball and socket balancing platform to avoid bending of specimen under compressive loading. The platform was placed horizontally on the test bed of MTS Servo Hydraulic Machine using spirit level. Two extensor meters were fixed on the front and back of test specimen, connected to analogue-digital signal converter and data logger/processor for high speed collection of data on five channels. One channel recorded the applied load and four channels displayed the compressive strains induced in the tests specimen. The compressive load was gradually applied to determine the ultimate stress of test specimen.

ANALYTICAL CONSIDERATION:

The compression strength of the wave free laminates was determined experimentally from a cross ply laminate having twenty one 0° and twenty two 90° layers. The average compression strength of two wave free specimen was determined to be 101317.5 Pa. The rule of mixture was used to determined the compression strength of 0° and 90° layers and this information was used to determined the wave free compression strength for laminates having eight to fourteen 0° layers in the test specimen. This analysis assumes constant strain in the loading-direction in the laminate. Further, the stresses in the 0° and 90° layers are assumed to remain in the same proportion as their respective moduli of elasticity; where.

$$\epsilon_0 = \frac{\sigma_0}{E_0} \quad \text{And} \quad \epsilon_{90} = \frac{\sigma_0}{E_0}$$

$$\text{Therefore} \quad \sigma_{90} = \sigma_0 \frac{E_{90}}{E_0}$$

The ultimate compressive strength of wave free laminate;
The volume fraction of 0° fibers; V_0=21/43
The volume fraction of 90° fibers; V_{90}=22/43
The compression moduli of elasticity for IM7/8551-7A carbon-epoxy in a longitudinal direction;
E_0=22.3 GPa and in transverse direction, E_{90}=1.29 GPa

Solving for axial stress for failure in 0° fibers; $(\sigma_0)_{ulti}$ using rule of mixture;

$\sigma_c = \sigma_c V_0 + \sigma_{90} V_0$

$\sigma_c = (\sigma_0)_{ulti} V_0 + [(\sigma_0)_{ulti} E_{90}]/ E_0 V_{90}$

$(\sigma_0)_{ulti} = 195605.7$ Pa

and axial stress failure in 90° fibers; $(\sigma_{90})_{ulti}$ using following equation;

$(\sigma_{90})_{ulti} = (\sigma_0)_{ulti}\ E_{90}/E_0 = 11315.3$ Pa

For wave free laminates having eight, nine OR fourteen 0° layers, failure is defined to occur when the axial stress in the 0° fibers reaches the failure stress of 195605.71 Pa and the axial stress in 90° fibers reach 11315.3 Pa. Thus, compression strength for other wave free

Where η_0 and η_{90} represent volume fraction of 0° and 90° layers in the wave free laminate. The ultimate stresses determine experimentally in the wavy specimen were normalize by the allowable failure stresses in the given wave free laminate to calculate the strength ratio using LOTUS software as shown in Table-III. The wavy 0° layer fraction, f_w is defined as the number of wavy 0° layers divided by the total number of 0° layers within the laminate. A constant severity of layer wave severity parameter, δ/λ, signified by the wave amplitude, δ divided by the wave length, λ as shown in Fig-3 was attempted. The compression strength ratio, f_s is defined as the compression strength of the specimen of non dimensionalzed by the average compression strength of the corresponding wave free laminate. The fraction of wavy 0° layer, f_w have been plotted against compression strength ratio, f_s in Fig-4.

laminates, $(\sigma)_{ulti}$ were calculated using the following relationship and given in Table-II

Table-II: Compression strength of equivalent wave free laminates calculated in analytically

Laminates	No. of 0° Layer	Comp. strength, (Pa)
DNW-1, DNW-2, DNW-5	14	100283
DNW-6	13	100048
DNW-4, DNW-7	12	99774
DNW-9	10	99072
DNW-8	8	98040

$$\sigma_{ulti} = \frac{\eta_0\, \sigma_f + \eta_{90}\, \sigma_{90f}}{\eta_0 + \eta_{90}}$$

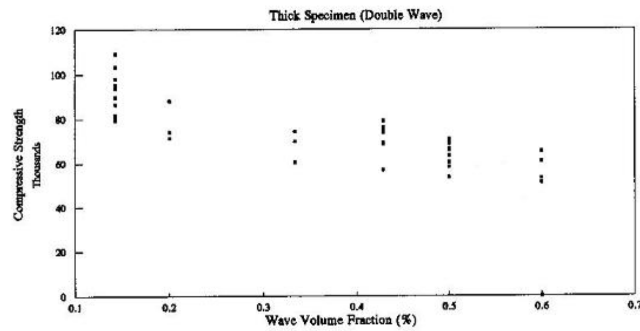

Fig.-4: Graph showing influence to wave fraction on compression strength ratio.

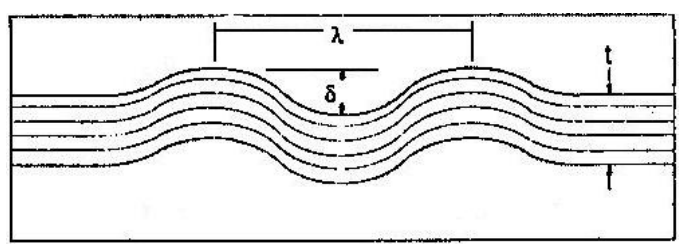

Fig.-3: Layer wave geometry parameters

Table-III: The compression strength ratios of test specimens having Double Nested Waviness, (DNW).

Panel No.	Wave Severity	Modulus $E(10)^6$	Ulti. Strain	Ulti. Stress, Pa	Strength Ratio, f_s
DNW-1A	0.050658	14.4058	0.7935	98182	0.979049
DNW-1B	0.047757	14.2149	0.701745	85240	0.949712
DNW-1C	0.051364	13.8563	0.694485	93624	0.933597
DNW-1D	0.063956	13.7574	0.816915	109131	1.088230
DNW-2A	0.057404	10.7994	0.8965	86525	0.862808
DNW-2B	0.0566	11.2056	0.9077	94408	0.941416
DNW-2C	0.056264	11.209	0.9063	94309	0.940429
DNW-2D	0.057317	10.9308	1.042	103483	1.03191
DNW-3A	0.058373	--	--	88049	0.88732
DNW-3B	0.056971	--	--	71319	0.719866
DNW-3C	0.059335	--	--	74011	0.747038
DNW-3D	0.061156	--	--	87939	0.887622
DNW-4A	0.065379	11.43052	0.62	60417.29	0.605537
DNW-4C	0.058049	11.54296	0.6933	74207.38	0.74375
DNW-4D	0.056349	11.63319	0.588	69829.53	0.699872
DNW-5A	0.044231	14.9682	0.650925	78939	0.787162
DNW-5B	0.04788	13.448	0.55836	76275	0.760598
DNW-5C	0.048421	15.0543	0.43824	68437	0.682439
DNW-5D	0.050099	12.4241	0.4673	56928	0.567673
DNW-6A	0.04907	11.4317	0.5473	74098	0.740627
DNW-6B	0.045682	11.2991	0.6919	75728	0.756919
DNW-6C	0.050179	11.6453	0.6518	73698	0.736629
DNW-6D	0.046238	11.1966	0.5615	69092	0.690591
DNW-7A	0.066208	11.63738	0.5248	58303.23	0.584349
DNW-7B	0.061246	12.25236	0.5248	63245.09	0.633879
DNW-7C	0.06115	11.78193	0.5248	69261.38	0.691478
DNW-7D	0.064303	11.8492	0.5248	65751.53	0.659
DNW-7E	0.070198	11.59251	0.5248	53598.03	--
DNW-8A	0.0579	11.55306	0.627	60311.63	0.615173
DNW-8B	0.0544	11.18781	0.627	68579.1	0.6995
DNW-8C	0.059	11.24639	0.627	70804.17	0.722196
DNW-8D	0.0582	11.8961	0.627	55531.25	--
DNW-8E	0.0601	11.67583	0.627	66415.69	0.677434
DNW-9A	0.062781	11.50341	0.602	64380.75	--
DNW-9B	0.059491	12.04849	0.602	65172.17	0.657822
DNW-9C	0.067205	11.06406	0.602	60739.18	0.613078
DNW-9D	0.06237	10.69569	0.602	53201.04	0.536991
DNW-9E	0.068165	10.95433	0.602	51288.4	--

DISCUSSION:

It has been observer from the graph regarding fraction of wavy 0° fibers and compression ratio of laminate that has the volume fraction of the wavy 0° layers, f_w increase from 0 to about 0.35, there is drastic reduction in compression strength ratio, f_s of laminate from its maximum value to about 0.6. After fw of about 0.35, the compression strength ratio, f_s stabilizes a constant value of about 0.6. At the ultimate point, the wavy 0° layers give up first and they no longer participate in the load sharing mechanism. At failure, the compression strength of the laminate in terms of load-carrying capacity of the wavy 0° layers reduces to zero. Since the remaining 0° layers dominate the load carrying capacity of cross ply laminates. Fw provides an estimate of deterioration in the compressive strength of laminate. Thus, estimating compression strength reduction by simply eliminating the contribution of the wavy 0v layers appears to be a suitable technique under limited conditions.

The failure of all the test specimens in compression tests was found to be sudden and catastrophic. The brittle of the test specimen followed by crushing of their mating surfaces damage the surface morphology of test specimens which made it impossible to determine the crack initiation. Post-failure brooming, characterize by through-the thickness splaying of the layers and by numerous delimitations was most pronounced in the thinner specimens as shown in Fig-5. An angled fracture plane through the specimen thickness was evident in several failed specimen suggesting the presence of a shear initiated failure mode. The wavy 0° layers commonly were fractured at OR near an inflection point of the layer wave as shown in Fig-6.

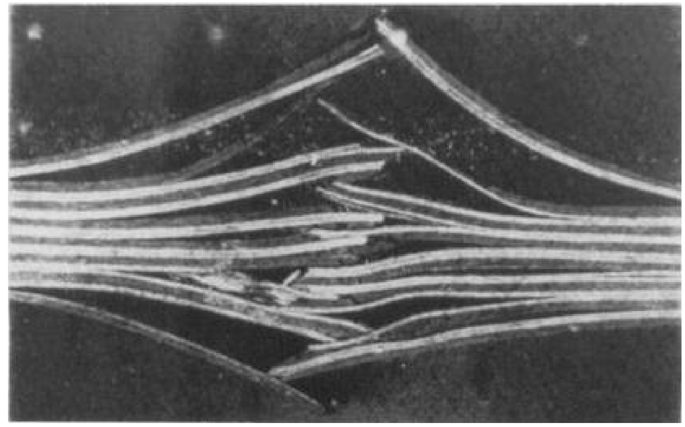

Fig.-5: Post compression test analysis of laminate.

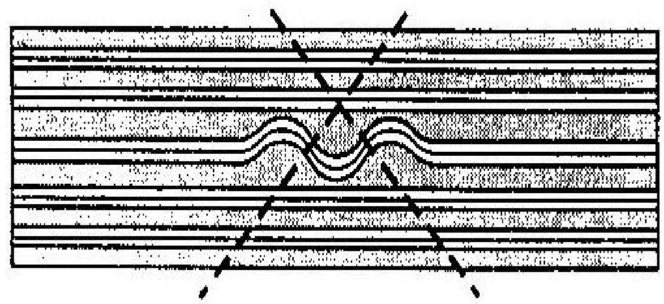

Fig.-6: Preferred angular orientation of failure planes in a wavy specimen.

CONCLUSION:

Laminates having different volume fraction of wavy 0° layers in double nest formation were produced in a single step fabrication procedure. The effects of multiple layer waviness on ultimate compression strength of wavy laminate was determined experimentally and rationalized analytically. Results suggest that the reduction in the compression strength in a composite laminate is of the order of volume fraction of the wavy 0° layers till its volume fraction is 0.35 and above that value, the reduction in the compression strength due to layer waviness is constant. The percent reduction in compression strength in the laminate was found to be of the order of wave fraction of wavy 0° layers under restricted conditions.

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REFERENCES:

1. H.J Garala: David Taylor *Research Center Report TDRC*-89/016, Bethesda, MD, (1989)
2. H.E Gasconigne and M.G Abdullah: In 'Proc. First Joint Mechanics Meeting of ASME', Nonlinear Effects, AMD *American Society of Mechanical Engineers*, 159 (1993), 187.
3. D.O Adams D.O and M.W Hayer*: Journal of Reinforced Plastics and Composites*, 12 (1993), 414.
4. T.A Bogetti, J.W Gillespic and M. Lamontia: *Journal of Thermoplastic Composite Materials*, 5 (1992), 344.
5. Z.M Khan: *Proceedings of 18th International Summer College on Physics and Contemporary Needs*, 10-17 Jun, Nathiaguli, Pakistan (1993).