Low Velocity Impact Response of the Filament Wound Anisogrid CFRP Cylindrical Shells

Suresh Paramasivam (✉ suresh.me2004@gmail.com)

Muthayammal Engineering College, Rasipuram

Anish Jafrin Thilak Johnson

Mepco Schlenk Engineering College

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Abstract

This work presents the experimental and finite element simulations to investigate the behavior of both unstiffened and anisogrid composite lattice cylindrical shells under low velocity axial impact. Impact damage has been an epidemic problem for composite structures. Even subjected to a low velocity impact, composite may sacrifice its load carrying capacity considerably due to various modes of failure. The test coupons fabricated as per American Society for Testing of Materials (ASTM) standards were put through Infrared (IR) thermography to find the imperfections during fabrication. The test coupons without defects were only taken into account for material characterization. Finite Element simulations are carried out on both the unstiffened and anisogrid shell structures using LS-DYNA® for a series of low velocity impacts. Also these shell structures were subjected to impact load experimentally for the validation of the results. The results of these studies indicate that the anisogrid model presented in this work possess greater load carrying capacity than unstiffened shell under dynamic loading conditions, also the weight of the structure has been drastically reduced.

1. Introduction

Composite materials are substance consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties than those of the individual components used alone. Because of the high strength to weight ratio and damage tolerance composite materials, especially carbon fiber reinforced polymer (CFRP) shell structures are finding many applications in aerospace applications [1]. The loads which can occur during its service life must be taken into account for a stable and reliable structural design. Low-velocity impacts are considered potentially dangerous for a composite shell structures, even subjected to a low velocity Impact, these shell structures may sacrifice its load carrying capacity due to various modes of failure [2]. Several areas have been accounted which are not fully exploited and restrict potential advancement of weight-efficiency of composite structures namely, post-buckling capabilities, imperfection robustness and loading dynamics. Many works concerned with the buckling response of thin cylindrical shells have been published and the different modes of failure [3–7], have been described. In this work low velocity impact response of composite cylindrical shell structures have been analyzed by means of experimental testing and numerical simulations

Vasiliev et al investigated the history of the lattice structures [3] development and made the founding studies on fabrication techniques. They proposed that the modern unidirectional carbon composites, being loaded along the fibers, are characterized with specific strength and stiffness than the corresponding characteristics of aluminum alloys. The anisogrid composite lattice structures are thin walled cylindrical shells [4], [5] composed of both helical and circumferential ribs articulated in such a way that confined defects in the grid do not grossly affect the universal behavior of the structure. Buragohain et al carried out a study of filament wound [6], [7] grid-stiffened composite cylindrical structures. The composite lattice structures have been considered as the excellent replacement for conventional solid and honeycomb structures.

Morozov et al have reported that Anisogrid composite shells [8] are used in various structural applications, such as rocket interstages, payload adapters for spacecraft launchers, fuselage components for aerial vehicles, and components of the deployable space antennas. Recently, Buragohain et.al reported the optimal design of filament wound grid-stiffened composite cylindrical structures. According to them the grid of stiffening ribs that are made by filament winding makes such a structure very highly efficient and reliable. Zhifeng Zhang et.al demonstrated a progressive failure [9] methodology to simulate the initiation and propagation of multi failure modes for advanced grid stiffened (AGS) composite plates/shells on the basis of a stiffened element model.

Polymer matrix composite laminates are prone to delamination when impacted, resulting in low damage tolerances, which is of great concern for load carrying applications. The impact behavior of composite materials has been investigated by many authors [11], [12]. Damages in composites are different from those in metals. Composite failure is a progressive accumulation of damage, including multiple damage modes and complex failure mechanisms [13], [14]. Our earlier investigations [15] proved that the anisogrid shell structure deliver more energy absorption than the unstiffened shell structure under static loading condition. Recently, the effects of impact energy levels, impact locations and changes in layer thickness of 3D printed thermoplastic plates were studied [30]. In addition to the available literature on anisogrid shell structures over the past decades, this paper present another more recent approach to the experimentation and numerical simulation of CFRP shell structures. The objective of this study is to compare the impact response of the CFRP shells plain cylinder and anisogrid, when they are dynamically loaded in axial direction. The developed numerical models were validated with the obtained experimental results. The present paper deals with the following phases of work:

- i. Infrared thermography Nondestructive testing (IRNDT) of the CFRP test coupons followed by material characterization as per ASTM standards for the estimation of unidirectional elastic and strength properties.
- ii. Fabrication of CFRP cylindrical shell structures viz., unstiffened (plain cylinder) and anisogrid using newly developed filament winding machine.
- iii. Experimental and Finite element analysis (FEA) of unstiffened and anisogrid CFRP cylindrical shell structures under axial impact.

2. Materials And Methods

2.1. Materials

The matrix and reinforcement selected for the fabrication of the CFRP test specimens and composite shell structures are epoxy and carbon fiber respectively. Carbon fiber is composed of carbon atoms bonded together to form a long chain [1]. Properties of carbon and epoxy used for the fabrication of CFRP

composite shell structures are shown in Table 1. Epoxy resin possess better mechanical properties in tension, compression and impact than polyester resins hence they are preferred in aerospace applications. For enhancing the performance of resin (epoxy), hardener (HY 951) is used in ratio 1:10. For the fabrication of anisogrid composite shell structure polyurethane foams are used. Wooden and foam mandrels were prepared as per the structural geometry of anisogrid shell structures to perform filament winding process.

Table 1
Properties of Fiber and Resin

Carbon Tow		Matrix	
Filament Diameter, μm	7	Type	Epoxy
Thickness, mm	0.25	Curing Temperature	20 ⁰ C – 180 ⁰ C
Weight per sq. meter, g/m ²	640	Density, kg/m ³	1.06 x 10 ³
Tensile Strength, MPa	225	Tensile Strength, MPa	33
Density (gm/cm ³)	1.74	Compactible Hardener	HY 951

2.2. Structural Geometry

The actual dimensions of rocket interstage structure [7] are 10 m in diameter and 14.5 m in length with a thickness of 0.28 m. For performing FEA simulation the interstage structure is modeled with a scale of 1:70 and their specifications are listed in the Table 2.

The scaled structure is modeled [16] in Solidworks® 2018 as shown in Fig. 2 & Fig. 3. The circumferential ribs are arranged in such a way that it passes through the centre of the helical ribs in order to reduce the deformation of the shell structure. The ribs are considered as the main load bearing members in the anisogrid shell structure.

Table 2
Specimen configuration

Properties	Anisogrid	Unstiffened
Outer diameter (mm)	140	140
Height (mm)	205	205
Shell thickness (mm)	4	4
Distance between helical ribs (mm)	73.26	-
Distance between circumferential ribs (mm)	68.33	-
Helical rib thickness (mm)	5	-
Circumferential rib thickness (mm)	4	-

2.3. Fabrication of Test Coupons

Fibers are commercially available in small diameter, ranging from 5 to 7 microns for carbon fibers. Fibers (single filament) together are gathered in the form of a tow. The specimens were prepared by the combination of impregnation and hand layup process in which the impregnated carbon fiber was wound over the wooden plate. Impregnation refers to partially cured mixture of fiber and resin. The unidirectional impregnated fibers can be cut and stacked to form the final product. The fiber and resin hardener mixture are taken in the ratio 1:1.

A wooden plate of appropriate dimensions was selected and pins were hammered in at the appropriate locations depending on the fiber width and specimen size as shown in Fig. 4. Once the pins were placed on the mold a layer of Mylar sheet (release film) was placed on to it in order to facilitate the easy removal of the sample after curing. Pressure rollers are used for the uniform distribution of the resin and to remove the excess content. After curing the rectangular plate is sized into ASTM standards (D3039 & D3518) by means of cutting tool as shown in Table 3.

Table 3
CFRP Test Coupon Configuration

Sample No.	Standard	CFRP test coupon configuration	Range of thickness, mm	Quantity
1	ASTM D3039	Coupon without end tab	2.2–2.6	3
2	ASTM D3518	Coupon without end tab	2.25–2.6	3

2.4. Fabrication of unstiffened shell

Filament winding is a comparatively simple method for the fabrication of cylindrical shells using continuous tows. Carbon tows and epoxy resin mixture are taken in 1:1 ratio for the fabrication of the shell. A wooden mandrel was prepared according to the unstiffened shell dimensions and fitted in the filament winding machine. Impregnated carbon tows are wrapped around a rotating mandrel and cured under room temperature to produce unstiffened cylindrical shell. Release film is wrapped over the wooden mandrel for easy ejection and good surface finish.

Table 4
CFRP Unstiffened Shell Configuration

Specimen No.	Wall thickness (mm)	Shell weight (gm)	Fibre volume fraction (%)
US 1	2.09	177	51.3
US 2	1.98	157	48.17
US 3	1.89	150	42.75
US 4	1.97	156	47.38

The impregnated carbon tows are wound as per the required dimensions and allowed to cure in the room temperature to get the final structure as shown in Fig. 5. The winding operation is achieved by manually rotating the handle as shown in Fig. 6 whereas the grooved mandrel is replaced by plain wooden mandrel. Totally four CFRP unstiffened shell structures are fabricated with the configuration shown in Table 4. The effect of pretension during the filament winding process on mechanical properties of finished component were studied earlier [29]. In addition there is an effect of the fiber orientation on the behavior of continuous carbon fiber composites [30], so that in this study the helical ribs angle was selected properly.

2.5. Fabrication of Anisogrid shell

The anisogrid shells are also fabricated by means of filament winding, where the plain wooden mandrel is replaced with a foam mandrel for easy removal after curing. The main objective of the fabrication is to control the configuration of the lattice ribs both helical and circumferential.

Table 5
CFRP Anisogrid Shell Configuration

Specimen No.	Wall thickness (mm)	Shell weight (gm)	Fibre volume fraction (%)
AS 1	3.10	126	42.83
AS 2	3.27	137	49.37
AS 3	3.18	130	46.59
AS 4	3.05	123	42.06

A low density foam mandrel is grooved as per the anisogrid shell CAD model as shown in figure 7. Silicon spray is applied on the grooved surface for creating a non-sticky layer between the foam mandrel and impregnated carbon tows. Proper placement of the fibers along the grooves cut on the mandrel surface is important in any filament winding activity to get the required structure (figure 8). The guide wheels are used for aligning the carbon tow inside the grooves along the circumferential or helical direction of the mandrel. The tension of filament winding must be strictly controlled in order to minimize the buckling of the shell. The CFRP anisogrid shell configurations are shown in Table 5. Recently, an innovative method is proposed for the production of three-dimensional cylindrical lattice structures using autoclave [28]. They have designed an out-of-autoclave compaction process which uses the compression of a heat-shrink tube during its shape recovery in oven.

3. Experimental Procedures

3.1. Lock-In Thermography Experiments

Inspection of composite materials using Infrared thermography has been increasing in the recent years. IR thermography has the possibility of inspecting large surface areas rapidly.

Lock-in IR thermography technique has been chosen in this study for the inspection of CFRP test coupons for locating the defects like delamination, voids, debonds, wrinkles, inclusions, broken fiber, and fiber misalignment. The process of IR thermography testing of CFRP test coupons is based upon the principle of thermal imaging. It involves dynamic stimulation which can be applied by halogen lamp, ultrasonic and by mechanical means. Figure 9 and Fig. 10 describes the working principle of lock-in thermography. The specimens which are sized to ASTM standards are examined in order to locate any imperfections present in them. A uniform heat source using a hot air blower is applied on the bottom surface of the CFRP test coupon and the top surface is filled with water. So that any cracks or defects present in the specimen can be located as water inclusion areas or temperature variation zones using the IR camera (Fluke Thermography Model Ti32). Finally the digital data from the IR camera is acquired and stored on a personal computer for the subsequent analysis.

3.2. Material characterization

For the evaluation of unidirectional mechanical properties, stress transfer, distribution of load, and to govern the damage accumulation and propagation material characterization is essential. The main objective of mechanical testing of composite material was to determine the basic properties like longitudinal modulus, ultimate tensile strength, in-plane shear strength, shear modulus and Poisson's ratio for the finite element analysis of the shell structures. The mechanical testing was carried out using the FIE make UTE-40 Universal Testing Machine (UTM) with a capacity of 400kN and 5mm/min as feed rate. The test coupons fabricated as per ASTM (D3039 & D3518) standards were fitted in the UTM as shown in Fig. 11 and an axial tensile load is applied. The measurement of displacement is based upon an electronic extensometer with a standard gauge length of 50 mm. In the UTM test setup, the carbon-fibre-reinforced epoxy composite test coupon is aligned in such a way that the tensile loading direction is in accordance with the fiber length direction for the estimation of unidirectional mechanical properties longitudinally. Poisson's ratio has been estimated by carrying out tensile tests with the assistance of electrical strain gauges employed at a distance of 25 mm wide.

3.3. Impact testing

Low velocity impact tests were performed on both the unstiffened and anisogrid shell structures by subjecting them to an axial impact load within a short interval of time. For low velocity impact testing, common features of impact loading are the vibratory load responses from the composite shell specimen, the impactor plate and the specimen supporting fixture (base plate). A controlled impact is achieved by dropping a square shaped impactor plate (250mm×250mm×20mm) which is attached to an electromagnet from the prescribed impact heights as shown in Fig. 12. The impact parameters like resultant displacement, velocity and acceleration of the shell structures at the time of loading were recorded by means of electronic modules viz. digital instruments (height gauge, velocity meter, acceleration meter, displacement meter), analog modules (load cell amplifier, analog to digital converter), micro controller module (micro controller based data acquisition system) and data acquisition software. The overall impactor mass was 81.69 kg, four different drop heights of 0.46, 0.82, 1.275, and 1.835 m were chosen, corresponding to nominal impact velocities of 3, 4, 5 and 6 m/s respectively. The shell was placed on a rectangular steel base resting on the three load cells (Model: CR034HO, Capacity: 30 Ton, Gauge: 350 ohms, IPA Make) used for measuring the contact force history. The charges generated at the time of impact were converted into potential difference using the load cell amplifier in the data acquisition system.

The height gauge includes 20 magnetic read switches which are located along the vertical column at a distance of 10 cm wide. A microcontroller with an electromagnet was used for evaluating the height of the impactor. The actual velocity of the impactor before and after collision was evaluated by velocity meter arrangement. It comprises two inductive type proximity switches (30 mm diameter; sensing distance-15 mm) located approximately 30 mm above the specimen surface and are placed at a distance of 20 cm between them. The data acquisition system shown in Fig. 12 includes an amplifier, an analog to digital converter (ADC) and a micro controller (AT89C2051).

4. Finite Element Modelling

4.1. Impact analysis using LS-Dyna®

Both the anisogrid and unstiffened structure CAD models were imported and analysed individually using LS-Dyna®, explicit FEA software which is capable of predicting the crushing mode of thin-walled carbon/epoxy composite shells under axial impact loading.

Finite Element Analysis was implemented with the descriptions given in Table 6. The bottom plate (Base) and top plate (Impactor) as shown in Fig. 13 were given the properties of steel and for composite shell structures the unidirectional mechanical properties which are estimated in material characterization are used. Automatic topology mesh is chosen for the shell structures with an average mesh size of 7mm. The termination time for the motion of impactor plate varies for different drop velocity. The impact parameters such as displacement, velocity and acceleration were plotted with respect to time. The drop plate is given the impact velocity and an automatic surface to surface contact type is assigned for the shell and the drop plate.

Table 6
FEA description

Parts	Material Model	Element Type	Mesh size	Mesh type	Boundary Conditions	Material Property
CFRP Shell	Composite Damage	Shell	7	Automatic topology mesh	$x = 1, y = 1, z = 1,$ $\theta_x = 1, \theta_y = 0, \theta_z = 1$ (applied for shell bottom nodes)	$\rho = 1.74e^{-9} \text{T/mm}^3$ $E_1 = 25.566 \text{ GPa}$ $\nu_{12} = 0.305$ $G_{12} = 9.770 \text{ GPa}$
Drop plate	Rigid	Solid	7	Automatic topology mesh	$x = 1, y = 0, z = 1,$ $\theta_x = 1, \theta_y = 1, \theta_z = 1$	$\rho = 7.83e^{-9} \text{T/mm}^3$ $E = 210 \text{ GPa}$ $\nu = 0.3$
Base plate	Rigid	Solid	7	Automatic topology mesh	$x = 1, y = 1, z = 1,$ $\theta_x = 1, \theta_y = 1, \theta_z = 1$	$\rho = 7.83e^{-9} \text{T/mm}^3$ $E = 210 \text{ GPa}$ $\nu = 0.3$

5. Results And Discussions

5.1. Lock-In Thermography results

The heat dissipation pattern & resulting indications on IR camera screen were observed and interpreted carefully. During continuous heating of CFRP test coupons, the thermal energy from the heated bottom surface diffuses throughout the body of the specimen. Defect areas exhibit irregular temperature distribution behavior, which will appear in the temperature contours of the IRNDT. The artificial defects (flat bottom holes) show water presence as dark indication. Figures 14 and 15 shows the CFRP test coupons without and with defects. The dark indications present in 45⁰ laminate may be because of fiber misalignment, absence of resin or due to uneven distribution. The temperature contours and IR Thermography test results of all the tested samples are not included in this paper just for the sake of brevity.

5.2. Material characterization results

From the material characterization results given in Table 7 we can easily conclude that the unidirectional carbon/epoxy composite test coupons withstand a maximum load of 13.36 kN with ultimate tensile strength of 238.14 MPa and possess shear strength of 78.2 MPa. These material properties can be incorporated in the present work for performing both experimental and finite element analysis. The specimens after failure indicates that the breakage have been happened only along the matrix direction. The experimentally observed unidirectional elastic and strength properties of the CFRP material have been incorporated into the finite element model.

Table 7
Consolidated material characterization results

Sample ID	ASTM	F _{max} (kN)	A (mm ²)	Tensile Strength (MPa)	Tensile Modulus (GPa)
1	D3039	10.94	49.25	227.96	22.98
2	D3039	13.36	50.12	238.14	25.566
3	D3039	12.61	49.20	276.74	28.63
Sample ID	ASTM	F _{max} (kN)	Area (mm ²)	Shear Strength (MPa)	Shear Modulus (GPa)
1	D3518	2.82	49.58	78.2	9.770
2	D3518	2.50	49.15	74.5	8.592
3	D3518	2.78	50.25	76.1	8.347
Poisson ratio		0.305	0.306	0.3065	

5.3 FE Analysis Results

Finite element modelling of Unstiffened and Anisogrid shell structures are carried out using LS-Dyna® in which each node is associated with three translational and rotational DOF. The impact parameters such as displacement, velocity and acceleration of the entire shell structures are plotted with respect to time. In case of unstiffened shell structure (Fig. 16.a), when subjected to an axial impact the displacement of nodes at the centre region of the shell is high which will leads the structure to buckle easily. While in the case of Anisogrid shell structure (Fig. 16.b) the displacement of the nodes in the helical ribs are controlled by circumferential ribs which reduces the tendency to buckle. Also the displacement, velocity and acceleration plot easily reveals that the rate of buckling was very much reduced in the case of Anisogrid shell structures. At the same time the weight of the structure can be reduced up to 51.27%. The entire displacement, acceleration, velocity and energy plot are not included in this paper just for the sake of brevity. Figure 17 reveals that for a drop velocity of 3m/s and 4m/s the drop plate gets in contact with the shell at a time of 155μsec and 204μsec respectively. It was clearly observed that the unstiffened shells deforms at a faster rate than that of anisogrid shell. The velocity plot (Fig. 18) shows that there is fluctuation in deformation rate (velocity) of the unstiffened shell which leads to sudden failure of the shell structure. Similarly the acceleration of the unstiffened shell attains a peak value readily than that of the anisogrid counterparts which implies that the unstiffened shells are very prone to failure under impact loading. Moreover it is revealed that the deformation of helical ribs in anisogrid lattice structure meanwhile decreases because of the clamping effect of hoop ribs [26]. Earlier it was found that anisogrid pattern possess a higher local buckling strength in comparison to the triangular cells or isogrid pattern with the

same design variables [27]. Now, within the scope of this work the next phase is to validate the developed numerical model in the light of comparison with experimental results.

5.4 Impact Results – Experimental and FEA

Impact experiments were carried out on both the unstiffened and anisogrid shell structures at four different drop velocities 3, 4, 5 and 6 m/s respectively.

The observations on the damaged shell structures after impact loading reveal that the shell damage consists of two modes of failure namely matrix cracking and fibre breakage. The impact energy or the energy absorbed by the anisogrid shell structures is quiet better when compared to that of unstiffened shells as in the case of numerical simulations. The primary impact failure mechanisms are a very complex combination of energy absorption mechanisms such as delamination, which is followed by matrix cracking and fibre breakage. The deformation of the shells increases as the drop velocity increases, the deformation of the anisogrid shells have been controlled by means of the interconnected helical and circumferential ribs. The various modes of failure of the CFRP cylindrical shells both the experimental results as well as the results of finite element modeling are compared in the Fig. 20.

Table 8
Correlation of Results

Specimen	Drop height, mm	Mass, kg	Impact Velocity, m/s	Peak Load, kN		Comp. Mm		Energy, J		
				Exp.	FEA	Exp.	FEA	Exp.	FEA	% error
US1	460	81.69	3	2.5	3.2	44.3	38.29	7058	6242.09	11.56
US2	820	81.69	4	2.87	3.45	73.2	91.34	7133	6431.83	9.83
US3	1275	81.69	5	3.4	3.87	80.1	97.22	7204	6427.41	10.78
US4	1835	81.69	6	3.68	4.1	93.5	97.12	7289	6543.33	10.23
AS1	460	81.69	3	4.1	4.56	36.2	28.76	7175	6353.46	11.45
AS2	820	81.69	4	4.5	5.4	74.3	81.15	7200	6402.96	11.07
AS3	1275	81.69	5	4.85	6.8	87.1	92.02	7294	6628.79	9.12
AS4	1835	81.69	6	9.8	10.6	99.4	94.36	7697	6943.46	9.79

In light of these results, we can conclude that rate of deformation increases wit impact velocity in both unstiffened and anisogrid. Whereas the energy absorption rate has been improved in anisogrid pattern in comparison to the other. So that by incorporating more number of hoop ribs at specific location the energy

absorption rate can be further improved, at the same time weight reduction factor should be considered. Here in this study the weight has been reduce to 51.27%. .

6. Conclusion

The deformation and energy absorption of unstiffened and anisogrid cylindrical shells are systematically studied in this paper. The results indicate that the deformation mechanisms of the anisogrid cylindrical shells are distinct from that of the unstiffened shells. The accuracy of the experimentation has been confirmed by numerical simulation at level of lattice and unstiffened cylindrical shell structures. This investigation reveals a number of remarkable features of anisogrid cylindrical shells, as summarized below:

- The overall manufacturing process of the unstiffened and anisogrid CFRP shells presented in this paper is made cheaper by means of manual filament winding manufacturing process.
- IRNDT temperature contours infer that the infrared radiation is emitted inconsistently at the top surface due to the interruption of the flow of heat into the carbon/epoxy test sample by the defects.
- Material characterization was made on the CFRP test coupons for the estimation of unidirectional elastic and strength properties.
- FEA results demonstrate that for a drop velocity of 4m/s the maximum displacement of the anisogrid shell is 6 mm where in the case of unstiffened shell is 22.96 mm at an impact time of 204 μ sec without causing a significant damage in the shell structure.
- The impact behaviors of the CFRP composite shells have been experimentally analyzed. It has been experimentally observed that the modes of collapse and shell compression heights for Anisogrid shells under impact loading are much lower than the unstiffened counterparts. Also, the energy absorption capabilities are quiet better when compared to that of unstiffened because of the interconnected circumferential and helical ribs.

The experimental and Finite Element procedures for impact loads described in this paper would be useful in the development of lattice shell structures in aerospace applications. From the above conclusions, it is clearly shown that thin-walled shell structures made out of CFRP material would be used for energy absorption in impact applications, which contributes to the growth and welfare of spacecraft industries. Overall, the obtained results recommend the likelihood to explore more efficient design of grid structures whose energy absorption rate is still higher.

Notation

A	:	Area of cross section, mm ²
a _c	:	Spacing of hoop ribs, mm
ADC	:	Analog to Digital Converter
AGS	:	Advanced Grid Stiffened
a _h	:	Spacing of helical ribs, mm
AS	:	Anisogrid Shell
ASTM	:	American Society for Testing and Materials
b _c	:	Width of hoop ribs, mm
b _h	:	Width of helical ribs, mm
CAD	:	Computer Aided Design
CFRP	:	Carbon Fibre Reinforced Plastic
DOF	:	Degrees of Freedom
FEA	:	Finite Element Analysis
F _{max}	:	Maximum Load, kN
h	:	Drop Height, mm
H	:	Thickness of ribs, mm
IRNDT	:	Infra-Red Non Destructive Testing
US	:	Unstiffened Shell
UTM	:	Universal Testing Machine
v	:	Impact velocity, m/s
φ	:	Helix angle, degree

Declarations

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ETHICAL APPROVAL

Not applicable

CONSENT TO PARTICIPATE

Not applicable

CONSENT TO PUBLISH

The authors confirm that the manuscript is the authors' original work and the manuscript has not received prior publication and is not under consideration for publication elsewhere. And we confirm that upon acceptance of the paper, we will publish the paper.

AUTHORS CONTRIBUTIONS

Experimental work for this study is done by both authors and the finite element studies we performed by Author – 1.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

AVAILABILITY OF DATA AND MATERIALS

The authors declare that the data generated during this study are included in this article.

References

1. Sanjay K (2002) Mazumdar “Composites Manufacturing”. CRC Press LLC
2. Robert MJ (1999) Mechanics of Composite Materials. Taylor & Francis
3. Vasiliev VV, Barynin VA, Razin AF (2012) Anisogrid composite lattice structures – Development and aerospace applications. Compos Struct 94:1117–1127
4. Valery V, Vasiliev EV, Morozov “Advanced Mechanics of Composite Materials” Springer 2010.M.
5. Vasiliev VV (2006) A.F. Razin “Anisogrid composite lattice structures for spacecraft and aircraft applications”. Compos Struct 76:182–189
6. Buragohain R, Velmurugan (2011) Study of filament wound grid-stiffened composite cylindrical structures. Compos Struct 93:1031–1038
7. Buragohain M, Velmurugan R “Optimal Design of Filament Wound Grid-stiffened Composite Cylindrical Structures” Defence Science Journal, Vol. 61, No. 1, January (2011) pp. 88–94

8. Morozov EV, Lopatin AV, V.A. Nesterov "Finite-element modelling and buckling analysis of anisogrid composite lattice cylindrical shells" *Composite Structures* 93 (2011)
9. Zhang Z, Chen H (2008) Lin Ye "Progressive failure analysis for advanced grid stiffened composite plates/shells". *Compos Struct* 86:45–54
10. Totaro G, Nicola FDe (2012) Recent advance on design and manufacturing of composite anisogrid structures for space launchers. *Acta Astronaut* 81:570–577
11. Li G (2010) Venkata Sandeep Chakka "Isogrid stiffened syntactic foam cored sandwich structure under low velocity impact". *Compos A* 41:177–184
12. Serge Abrate (2011) *Impact Engineering of Composite Structures*. Springer
13. Zhang Y, Xue Z, Chen L (2009) Daining Fang "Deformation and failure mechanisms of lattice cylindrical shells under axial loading". *Int J Mech Sci* 51:213–221
14. Hualin F, Fang D, Chen L, Daia Z (2009) Wei Yang "Manufacturing and testing of a CFRC sandwich cylinder with Kagome cores". *Composites Science Technology* 69:2695–2700
15. Vasanthanathan A, Nagaraj P "Correlation study of IR TNDT analysis with structural failure mode of carbon-fabric-reinforced epoxy composites" *Journal of Engineered Fibers and Fabrics*, Volume 10(2), 2015
16. Vasanthanathan A, Nagaraj P, Nivas SS (2013) Significance of material characterization in FE Modeling of glass fabric/epoxy composite shell structure using LS-DYNA®. *J Struct Eng* 40(2):185–195
17. Sham Tickoo (2013) *SolidWorks 2013 for Designers*. Purdue University Calumet, USA
18. American Society of Metals "Characterization and Failure Analysis of Plastics" ASM International
19. Sham T (2013) *Ansys Workbench 14.0 for Engineers and Designers*. Dreamtech Press
20. ASTM D3039M (1997) "Standard Test Method for Tensile properties of Polymer Composite Materials", American Society for Testing and Mat., Vol 15.03, 100 Barr Harbor Drive, West Conshohocken, PA 19428, USA
21. Hodgkinson JM (2000) *Mechanical Testing of Advanced Fibre Composites*. CRC Press, USA
22. Valerio G, Belardi P, Fanelli (2018) Francesco Vivio "Design, analysis and optimization of anisogrid composite lattice conical shells". *Composites Part B: Engineering* 150:184–195
23. Zhang B, Chen H, Zhao Z (2018) Hualin Fan, Fengnian Jin "Blast response of hierarchical anisogrid stiffened composite panel: Considering the damping effect". *Int J Mech Sci* 140:250–259
24. Belardia VG (2018) Structural analysis and optimization of anisogrid composite lattice cylindrical shells. *Composites Part B: Engineering* 139:203–215 P.Fanelli, F.Vivio "")
25. G.Totaro "Optimal design concepts for flat isogrid and anisogrid lattice panels longitudinally compressed" *Composite Structures* (2015) 129, 101–110
26. Belardia F (2018) Vivioa "Structural analysis and optimization of anisogrid composite lattice cylindrical shells". *Composites Part B: Engineering* 139:203–215

27. G.Totaro "Local buckling modelling of isogrid and anisogrid lattice cylindrical shells with triangular cells" Composite Structures (2012) 94, 446–452
28. Daniele Santoro D, Bellisario (2020) Fabrizio Quadrini & Loredana Santo "Anisogrid thermoplastic composite lattice structure by innovative out-of-autoclave process". The International Journal of Advanced Manufacturing Technology 109:941–1952
29. Nihat, Akkus (2017) Garip Genc "Influence of pretension on mechanical properties of carbon fiber in the filament winding process". The International Journal of Advanced Manufacturing Technology 91:3583–3589
30. Desu HPrasadP, Rossi A, Mankoo GK (2020) Kazem Fayazbakhsh "Experimental characterization of 3D printed thermoplastic plates subjected to low velocity impact". The International Journal of Advanced Manufacturing Technology 107:1659–1669

Figures

Figure 1

Detailed view of anisogrid shell

Figure 2

Anisogrid shell structure

Figure 3

Unstiffened Shell Structure

Figure 4

Schematic Sketch of Hand-layup Setup for Test Coupon Fabrication

Figure 5

CFRP Unstiffened Shell

Figure 6

Filament winding setup

Figure 7

Foam mandrel

Figure 8

CFRP Anisogrid Shell

Figure 9

Lock-in Thermography Schematic sketch

Figure 10

Experimental setup

Figure 11

UTM with CFRP test coupon

Figure 12

Drop mass setup

Figure 13

FE model of Unstiffened and Anisogrid shell

Figure 14

IR NDT temperature contours - CFRP 0° without defects

Figure 15

IR NDT temperature contours - CFRP 45° with defects

Figure 16

Deformed configuration. (a) Unstiffened shell, (b) Anisogrid shell

Figure 17

Resultant Displacement Comparison Plot At 3 & 4 m/s

(a) Velocity @4 m/s

(b) velocity @6 m/s

Figure 18

Resultant Velocity At 4 & 6 m/s

(a) Acceleration @4 m/s

(b) Acceleration @6 m/s

Figure 19

Resultant Acceleration Plot At 4 & 6 m/s

Figure 20

Comparison of Impact Test Results with FEA