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Optimization of Stiffness Properties of Composite Sandwich using Hybrid Taguchi-GRA-PCA

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Abstract: The composite sandwich structures provide the benefits of higher Strength to weight ratio, higher stiffness and flexural strength. The different properties of a sandwich structure depend on various design factors such as material of core and facesheet, thickness of facesheet and core, type of core and panel shape etc. In this study, four different factors i.e. Material of Honeycomb core, Core Height, Facesheet Thickness and Panel Width, with each having three different values have been chosen and a L9 Orthogonal has been generated using Taguchi Design in Minitab 18. After that, 9 different samples have been fabricated as per configurations of L9 OA. Then three point bending test has been performed on these samples and the values of Bending Stiffness, Rigidity and Equivalent Stiffness has been calculated .Then Taguchi Analysis has been performed on the output responses and optimum design parameters have been detected. After that PCA assisted Grey Relation Analysis has been performed on output responses and the values of optimum design parameters for sandwich structure has been obtained.

Keywords: Optimization of Stiffness Properties; Kevlar® Honeycomb Core; Hybrid Taguchi–PCA-GRA; Computational Analysis of Composite Sandwich.

1. Introduction

A structural composite sandwich is a unique form of a laminated composite consisting of 3 main elements i.e.

- Two thin and stiff faces one at top and bottom position.
- A thick, light core (of different shapes and design).

The facesheets and core are bonded with each other in such a way so that they can transfer load between the different components.

The face sheets act together to produce an efficient stress couple counteracting the external bending moment.

The core of sandwich structure opposes shear and stabilize the faces, available at the top and bottom of it, against buckling or wrinkling. It is pretty important that, the bond between the core and faces of the sandwich structure be strong enough to bear the stresses. For attaining high stiffness-to-weight and bending strength-to-weight ratio utilisation of low density core can be very effective[1)].

Materials and Material Properties for Sandwich Structure

a. Face sheets- Any material available in the form of thin sheet can be used to form the faces of a sandwich panel. Most widely used face materials can be of two types- metallic and non-metallic materials. Metallic facesheets are steel, stainless steel and aluminum alloys. Non Metallic materials include plywood, reinforced plastic and fibre composites.

The design of unequal ply count face sheets has higher stiffness to weight ratio when compared with the conventional symmetric sandwich structures[2)].The unit-cell models having shell elements equivalent to layered cell wall can be used for compression simulation[4)]. The thickness of facesheet has a larger impact on the flexural rigidity and sheet stress on the sandwich structure[5)]. The laminates with thinner skins can lead to core crushing[8)].

b. Cores- Mainly 4 types of cores are used in sandwich structures such as- Corrugated, Honeycomb, Balsa wood and Foams.

Most required property of a core of a sandwich structure is the low density to reduce the sandwich weight.

The sandwich structure is more affected by type of core material rather than the core layer thickness[19)]. So it can be concluded that the density, shear strength and modulus, thermal and acoustical insulation are the most important properties of a core. The stresses are highest between Land W directions so this direction is the panel's weakest direction. It has been observed that the weakest angle is

62° and the L-direction is the strongest direction[3].

FEM analysis is a very strong tool for the structural analysis of the mechanism[17]. The Honeycomb core can be made of metallic or non metallic materials such as –

1. Metallic Materials - Aluminum, Steel etc.

2.Non Metallic Material - Glass, Paper, and Aramid fibre mats, such as Nomex, Kevlar etc.

Due to the different manufacturing methods the different honeycombs have different in and out-of-plane properties. But, Nomex honeycomb core is weak in, out-of-plane direction.[4]

c. Adhesives The purpose of an adhesive in a composite sandwich structure is to provide a good bond between the materials components. The various adhesives that are used are:

Epoxy Resins Epoxy Resins are low temperature curing material, normally between 20°C to 90°C. They can be used without solvents and they have low volume shrinkage. The biggest advantage of use of epoxy is that due to the absence of solvents, epoxies can be used with almost every type of core material. The shear strength of most of the epoxies are about 20-25 MPa.

Also other adhesives are available such as-

- Phenolics
- Polyurethanes
- Urethane Acrylates
- Polyester and Vinyl ester Resins

The percentage of fiber affects the mechanical properties of the fiber-reinforced polymer composite[21]. So it is has been observed that the different properties of sandwich composite structure such as Stiffness and Flexural Strength depends on various design factors such as material of core and facesheet, thickness of facesheet and core, type of core and panel shape etc.

After thorough study of past work it has been observed that-

1. Not much work has been done on sandwich structure having the commercial Kevlar Honeycomb Core Material.

2. Not much research work has been observed on optimization of stiffness properties of composite sandwich structure using Hybrid Taguchi-GRA-PCA.

So here seems an opportunity to make an analysis of stiffness properties of sandwich structure having Kevlar Honeycomb core.

The main Objective of this research is to identify the best combination of the different design factors to achieve the highest flexural stiffness, bending rigidity and panel stiffness using Hybrid Taguchi-GRA-PCA.

In this study, four different factors i.e. Material of Honeycomb core, Core Height, Facesheet Thickness and Panel Width with each having three different values will be chosen and a L9 Orthogonal will be generated using Taguchi Design in Minitab 18. After that, 9 different samples will be fabricated as per configurations of L9 OA. Then "Three point bend" test has to be performed on these samples and the values of Bending Stiffness, Rigidity and Equivalent Stiffness has to be calculated. After that, Taguchi Analysis will be performed on the output responses and optimum design parameters will be detected. Then PCA assisted Grey Relation Analysis will be performed on output responses and again the optimum design parameters will be detected. So ultimately the objective of this research work is the multi-response optimization of stiffness properties of composite sandwich structure design parameters.

2. Experimental Work

2.1 Selection Of Different Design Parameters

Material- The following materials has been selected for face sheets, Core and Adhesive-

A. Face Sheet Material- Carbon fiber

B. Core Material- Non Metallic Materials

C. Adhesive –Epoxy

Design Parameters- The main design parameters of a composite sandwich structures are material of face sheet and core, Thickness of core, Thickness of face sheet the size of the sandwich panel to be tested. An increase in cell size leads to an increase in the shear modulus of the core which ultimately results in an increase in the stiffness of the sandwich beam and the failure of the specimen is due to the fracture of the core[24]. With hexagonal composite material weight saving is 39% as compared with other composite material[25].

In present research, the design parameters and their corresponding levels employed for fabrication of composite sandwich structure are-

1. Core Material- (Kevlar, Nomex and Polypropylene)

2. Core Thickness- (8mm, 10mm and 12.7mm)

3. Face sheet Thickness- (.4mm, .6mm and .8mm)

4. Panel Width - (40mm, 45mm, 50mm).

2.2 TAGUCHI DESIGN

Taguchi Design can be used as the process of optimum design of a sandwich structure and for determining the optimum geometry of the unit cell simultaneously with the material and geometric parameters of the face skins[22]. Different researchers and statisticians have proved that the Taguchi approach is the most helpful tool for single objective optimization.

Taguchi and GRA are best suited for finding optimum wear and friction force of the composite[6]. Multi-response optimization is a suitable method for optimization of different parameters[7], [9], [13].

Taguchi analysis has been used to prove that the uncarbonized eggshell content in AA 2014 alloy helps in improving the hardness of the composite[18].

Taguchi L9 orthogonal array has been utilized to investigate the tensile strength of Acrylo-nitrile butadiene styrene (ABS)[20].

Due to its suitability, Taguchi Design has been adopted here also and for this, 4 factors with each having 3 levels have been utilized. These factors have been entered in MINITAB 18 software and the following L9 OA has been received as shown in table 1 below.

Table1- L9 OA obtained through Taguchi Design

C. N.	Core Material	Core Thickness (mm)	F/sheet Thickness (mm)	Panel Width (mm)
1	PK2	8	0.4	40
2	PK2	10	0.6	45
3	PK2	12.7	0.8	50
4	PN2	8	0.6	50
5	PN2	10	0.8	40
6	PN2	12.7	0.4	45
7	PPL	8	0.8	45
8	PPL	10	0.4	50
9	PPL	12.7	0.6	40

2.3 Fabrication of Sandwich Panels as Pe Taguchi Design

The sandwich structures having the config ation as per Taguchi Design have been fabricated using the Vacuum Assisted Hand Lay-Up method. The figure 1 nicely shows the fabricated sandwich panel.

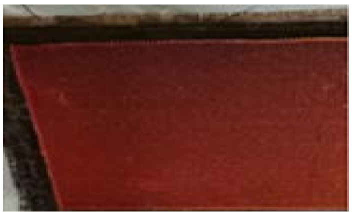

Figure 1 – Fabrication of Sandwich Panel

2.4 Three Point Bend Test of 9 Samples as per ASTM C393

The Three Points Bend Test has been performed for all the 9 configurations as per **ASTM C393 standard**[23] and the values of ultimate load and deflection has been calculated. The figure 2 and 3 show the testing set up and specimen after testing. Figure 3 shows a test specimen after the completion of a 3 point bending test. The failure of the core is main reason behind the failure of this composite sandwich panel. The tearing apart of the two walls from each other, results in failure of the panel.

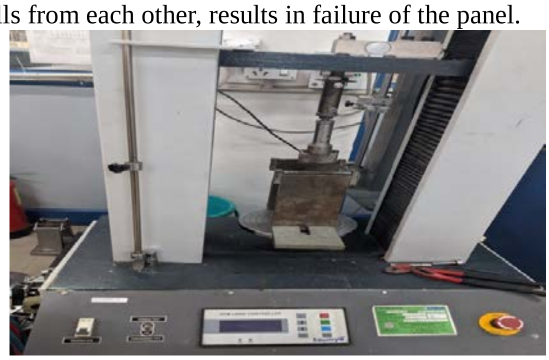

Figure 2- Three point Bend test Set

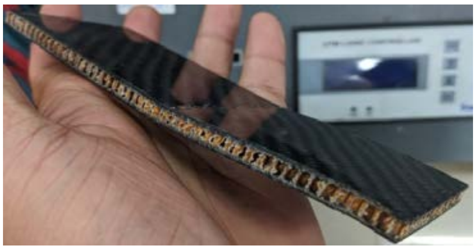

Figure 3- A Test Specimen after 3-Ponit Bend Test

3. RESULTS

The different sandwich properties i.e. Ultimate load, deflection and ultimately the Stiffness values, obtained for all 9 configurations have been noted and tabulated as shown below in table 2.

"Gibson and Ashbey Model" has been used for finding the different in and Out plane properties of the commercial honeycomb core [14]. The values of Bending Stiffness and Rigidity have been obtained by utilization of following formulae[16] for the two -

Bending stiffness, $D = E\,(d^3 - c^3)*b/12$ ....(1)

Shear panel rigidity, $U = G\,(d + c)^2 * b/4c$ ....(2)

Here c= Core thickness (mm)

t= Face-sheet thickness (mm)

d= Thickness of Sandwich (c+2t) (mm)

b= Sandwich Width (b) (mm)

L= Span length (150mm)

E= Face Sheet Young's modulus (E) (61340 MPa)

Plascore Data sheet [15] has been used to determine the-G= Shear modulus (G) of core. (98-102MPa)

Table 2- Values after Analysis of Test Samples

C. N.	Load (N)	Defor. (mm)	Stiffness (N/mm)	Bending Stiffness (MN mm^2)	Rigidity (N)
1	1078	2.832	380.650	34.65137	37749.6
2	1535.6	2.295	669.107	93.14356	54606.96
3	2181	2.03	1074.384	223.85	78927.17
4	1159.8	2.88	402.708	68.161	23112.5
5	1168	2.65	440.755	114.684	23328
6	1504	3.03	496.370	94.768	30403.35
7	396.5	1.48	267.905	85.738	10890
8	511	1.75	292.083	66.378	13520
9	535	1.61	332.298	130.293	13928.35

Failure of the Sandwich panel- After testing, the different sandwich panels have been thoroughly checked to determine the failure mode. It has been observed that the failure of the panel is due to Shear crimping which arises due to weak core in shear.

3.1 TAGUCHI ANALYSIS

For performing the Taguchi analysis, the three output response factors i.e. Panel Bending Stiffness (D), Bending Rigidity (U) and Equivalent Stiffness (S) have been selected and Taguchi analysis has been performed on individual output Parameters.

Table 3- Taguchi L9 OA with different responses

Core Code	CT mm	FST mm	PW mm	D $MNmm^2$	U N	S N/mm
PK2	8	4	40	34.6513	37749.6	380.650
PK2	10	6	45	93.1435	54606.9	669.107
PK2	12.7	8	50	223.85	78927.1	1074.38
PN2	8	6	50	68.161	23112.5	402.708
PN2	10	8	40	114.684	23328	440.755
PN2	12.7	4	45	94.768	30403.3	496.370
PPL	8	8	45	85.738	10890	267.905
PPL	10	4	50	66.378	13520	292.083
PPL	12.7	6	40	130.293	13928.3	332.298

Using Taguchi Analysis S/N ratio (signal to noise ratio) has been generated for all response characteristics i.e. Bending Stiffness (D) and Rigidity (U) and Stiffness and "Larger-is-better" option has been selected as the values more for the response factors will give a better sandwich structure.

Taguchi Analysis for Bending Stiffness (D), Rigidity (U) and Stiffness (S) for "Larger Is Better option"- Figure 4 shows "Main effects plot for Mean S/N ratios" for (D), (U) and (S). The S/N plots obtained from Taguchi analysis shows that the optimum (D), (U) and (S) are visible at Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm.

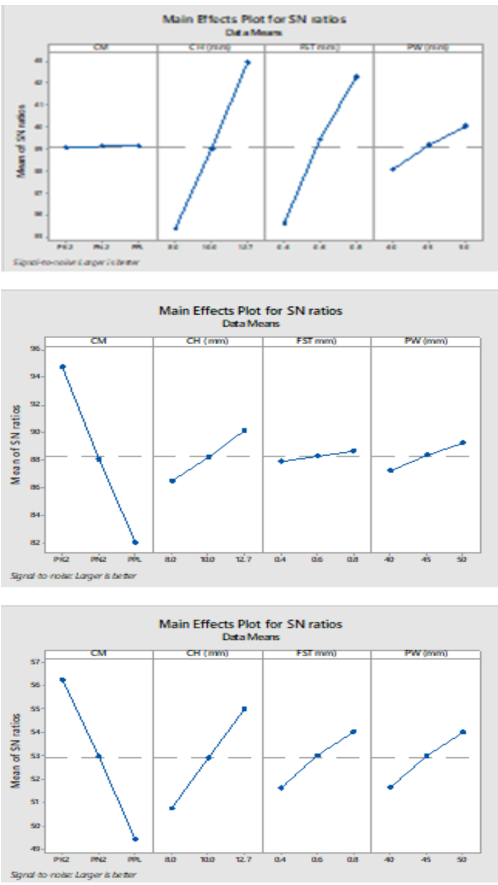

Figure 4- Main effects plot for SN ratios (D, U and S)

For static designs, Minitab offers following S/N ratios formula for the "Larger is better" option-

$$S/N = -10*\log(\Sigma(1/Y^2)/n) \quad \text{… (3)}$$

where Y= responses for the given factor level combination and n= number of responses in the factor level combination.

From the Taguchi analysis of all three responses, as shown above in figure 4, it has been observed that the optimum design has been achieved for Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm.

3.2 GREY RELATION ANALYSIS

GRA is a tool used for analysis of multi-objective function. The GRA has been performed here to validate or verify the results of the Taguchi Analysis.

GRA utilizes normalization of values to find GRC (grey relational coefficients) and GRG (grey relational grade)[12].

The aim of this research is to find the optimal process level for (D), (U) and (S) of composite sandwich structure. All these characteristics are of the "Larger-is-the better" type. For Larger the better, the most appropriate GRA formulae have been adopted for different optimum value requirement.

The Normalized values and Deviation Sequences have been found for all three response characteristics as shown in table.4. These two steps are necessary for calculating the GREY relation coefficients as the PCA can be performed only on the values of GREY relation Coefficients.

Table 4 - Normalized value and Deviation sequences of Response Characteristics

C. N.	RESPONSES			NORMALIZED VALUES		
	D	U	S	D	U	S
1	34.65	37749.6	380.65	0	0.394	0.139
2	93.14	54606.96	669.10	0.309	0.642	0.497
3	223.8	78927.17	1074.38	1	1	1
4	68.16	23112.5	402.70	0.177	0.179	0.167
5	114.68	23328	440.75	0.423	0.182	0.214
6	94.768	30403.34	496.37	0.317	0.286	0.283
7	85.738	10890	267.90	0.270	0	0
8	66.378	13520	292.08	0.167	0.038	0.029
9	130.293	13928.34	332.29	0.505	0.044	0.079

C. N.	DEVIATION SEQUENCES		
	D	U	S
1	1	0.6052	0.8602
2	0.6908	0.3574	0.5025
3	0	0	0
4	0.8228	0.8203	0.8328
5	0.5769	0.8171	0.7856
6	0.6822	0.7131	0.7167

7	0.7299	1	1
8	0.8323	0.9613	0.9700
9	0.4944	0.9553	0.9201

After Calculations of normalized values and deviation sequences, the Grey relation coefficients have been derived for three responses and tabulated in the table 5 as shown below.

Table 5- Values of Grey Relational Coefficients (GRC) for three responses

S. N.	Grey Relation Coefficients		
	D	**U**	**S**
1	0.33333	0.452397932	0.3675926
2	0.41987	0.583121146	0.4987398
3	1	1	1
4	0.37796	0.378685878	0.3751359
5	0.46425	0.379596487	0.3889012
6	0.42292	0.412134628	0.4109432
7	0.40650	0.333333333	0.3333333
8	0.37528	0.342150633	0.3401313
9	0.502770	0.343561656	0.3520741

3.3 PRINCIPAL COMPONENT ANALYSIS

(PCA) can be adopted in **GRA** to find out the weightage for each performance characteristics[10]. PCA can be utilized to find proper weight for different response characteristics to have an effective GRA[11]. The PCA can be used to determine the corresponding weighting values of different performance characteristics when GRA is applied to a problem having with multiple-performance characteristics. This always proves to be capable of objectively reflecting the relative importance of different performance characteristic[26]. Using the Hybrid Taguchi GRA assisted with PCA, the most dominating turning parameters for magnesium alloy on the multiple performances has been found as the depth of cut[27].So, here also by utilization of PCA, the weighted values for every performance characteristic have been identified. The multiple performance characteristics as shown in the table above showing GRCs of each performance characteristics has been entered in Minitab 18 and the corresponding Eigen values and Eigen-vector related to these Eigen value has also been generated. And ultimately the weighting contribution of each performance characteristic has been identified. The contribution of individual performance characteristics, such as, (D), (U) and Stiffness are shown in table below. The first principal component (PC1) variance contribution is as high as 96%, as mentioned in Table 6.

Table 6- Eigen Value Analysis of the Correlation Matrix

Principal Component	PC1	PC2	PC3
Eigen value	2.8795	0.1170	0.0034
Proportion	0.960	0.039	0.001

Table 7- Eigen vectors For Principal Component

Variable	PC1	PC2	PC3
D	0.568	-0.775	-0.278
U	0.576	0.615	-0.538
S	0.588	0.146	0.796

Table 8- Contribution Calculation for the PC

Performance Characteristic	Contribution/ Weighted Value
D	$(0.568)^2$ =.323
U	$(0.576)^2$ =.332
S	$(0.588)^2$ =.345

All the GR Grades has been generated by adopting PCA and the weighted value of all performance characteristic have been calculated as shown in table 9.

Table 9- Grey relation grades (GRG's)

Confi. No.	Grey Relation Grades (GRG)
1	0.128238835
2	0.164383929
3	0.333333333
4	0.125712423
5	0.137927049
6	0.13854314
7	0.119989853
8	0.117827263
9	0.134865042

3.4 Determination of Optimal Combination of Input Process Factors and Their Levels

GRG for each level of process factors has been evaluated to find out the optimum level of different process factors. The maximum value from the GRG has been chosen for each factor. In Table 10, the *BOLD ITALIC* values of GRG depict the largest value for the different levels of each process factor and Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm for optimum response characteristics.

Table 10- GRG Values C/P to Different Levels of Input Process Factors

Level	CM	CT	FST	PW
1	***0.20865***	0.124647	0.1282	0.133676
2	0.13406	0.140046	0.1416	0.140972
3	0.12422	***0.202247***	***0.1970***	***0.192291***

The GRA confirms that the optimum design has is available for Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm.

3.5 CONFIRMATORY TEST

The Table 11, shown below explains nicely that the results of Taguchi analysis and GRA for the response characteristics are in total agreement. Also it has been observed that the optimum values for Deformation for sandwich structure exists at ***Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm.***

Table 11– Comparison of results of GRA and Taguchi

INPUT FACTORS	TAGUCHI OPTIMAL VALUES	GRA OPTIMAL VALUES	LEVEL
Core Material	1	1	1 (PK2)
Core Thickness	3	3	3(.8mm)
FS Thickness	3	3	3(12.7mm)
Panel Width	3	3	3(50 mm)

Table 12– Values of D, U and S for optimized configuration

D ($MNmm^2$)	U (N)	S (N/mm)
223.85	78927.1	1074.38

The table 12 shows that the 3rd configuration from Taguchi Design has the highest values for the D, U and S as compared to all other Sandwich Panel configurations available in the Taguchi L9 OA. Ultimately it confirms that the Taguchi and GRA analysis are performed in a correct manner. So, the analysis shows that-

1. The stiffness is more for the Kevlar Honeycomb Core i.e. the Kevlar core can provide more stiffness then the other core materials.

2. The graphs of the Taguchi Analysis clearly show that the core height has the highest impact on the different stiffness properties as compared to other design factors. The analysis clearly supports the conclusion that with increase of the core height the stiffness can be enhanced in a significant manner.

3. Facesheet thickness also is an important factor after core height for achieving the higher stiffness values.

4. Panel width is least significant among the different design parameters chosen and it has same effect on all response parameters chosen here.

4. Conclusion

The different properties of sandwich structure such as Stiffness and Flexural Strength depends on various design factors such as material of core and facesheet, thickness of facesheet and core, type of core and panel shape etc. In this study, four different factors i.e. Material of Honeycomb core, Core Height, Facesheet Thickness and Panel Width with each having three different values has been chosen and a L9 Orthogonal has been adopted using Taguchi Design in Minitab 18. After that, 9 different samples have been fabricated as per configurations of L9 OA and "Three point bend" test has been performed on these samples. From three point bend test, the values of Bending Stiffness, Rigidity and Equivalent Stiffness has been calculated .After that, Taguchi Analysis has been performed on the output responses.

To calculate the weightage of effect of each process variable on stiffness properties, PCA has been adopted in calculation of GR Grades. The impact of all process variables has been reported systematically using this hybrid technique. It has been observed that the optimum stiffness for the sandwich panel exists at *Core Material PK2, Core Height 12.7mm. Face sheet Thickness .8 mm, and Panel width 50mm* and the values of Bending Stiffness D, Bending Rigidity U and equivalent Stiffness are 223.85MNmm^2, 78927.17N and 1074.384N/mm for this configuration. Also the composite fabricated using Kevlar® Honeycomb core and carbon fiber facesheet reported excellent stiffness performance for the optimized stiffness variables combination.

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Nomenclature

PCA	Principal Component Analysis
GRA	Grey Relation Analysis
OA	Orthogonal Array
PK2	Kevlar
PN2	Nomex
PPL	Polypropylene