DESIGN AND FABRICATION OF CORRUGATED SANDWICH
PANEL USING TAGUCHI METHOD

V.Diwakar Reddy¹, A. Gopichand², G. Nirupama³, G. Krishnaiah⁴

¹Associate Professor, ^{2,3}Research Scholar, ⁴Professor

Department of Mechanical Engineering,

Sri Venkateswara University College of Engineering, Tirupati

ABSTRACT

Open core metallic sandwich panels are novel type of structures, enabled by innovative fabrication and topology design tools. Flexural modulus is a basic property of the material in such fabricated open core structures welding by spot welding. In the present work spot welded metallic panels are used to optimize the geometry. Based on the analysis, panel structure parameters considered are Thickness of the sheet, Core height, Core shape, Panel size and Material constituents of panel face sheet, bottom sheet and core. The parameters are analyzed by Taguchi design of experiments by considering orthogonal array of L36. The main aim is to optimize the panel dimensions on flexural modulus of a fabricated metallic panel, using Finite Element Analysis. The problem is modeled in ANSYS and the flexural modulus is evaluated in the transverse direction by three point bending test (ASTM D790). The optimum dimensions are evaluated by Taguchi Analysis. The results show that the proposed approach can find optimal dimensions considering both better and more robust design.

Key Words: Taguchi, Corrugated panel, Sandwich panels, Flexural modulus

1. INTRODUCTION

The design of structures with optimal geometry includes sizing, shape and topology optimization. Extensive research is focused on shape optimization in the process of engineering design which has ample contribution towards cost, selection of material and time saving. The purpose of dimensional and shape optimization is to determine the optimal shape and dimensions of a continuum medium to maximize or minimize a given criterion such as weight to volume ratio, minimization of stresses, minimum deflection etc. Researchers are extensively

adopting the computer aided optimization in solving such problems. Earlier methods are various mathematical techniques which are complex and cumbersome. In the past few decades a number of innovative approaches are developed and widely applied in the design optimization such as genetic algorithms, practical swam analysis, Ant colony algorithm and many more.

Design of experiments (DOE) has become an important methodology that maximizes the knowledge gained for experimental data by using a smart positioning of points in the space. The methodology provides a strong tool to design and analyze experiments; it eliminates redundancy observations and reduces the time and resources to make experiments. Therefore, DOE statistical techniques useful in complex physical processes, such as determination of geometrical dimensions, Shapes, selection of material combination in many design processes. In the present study one such technique adopted is Taguchi method. In this method, the parameters identified for fabrication of corrugated panels are metal sheet gauge, core height, core materials, and core shape. The effect of individual parameters under three point bending is tested using Ansys workbench.

2. LITERATURE REVIEW

Ziad K. Awad, et al [4] presented his research aimed to develop an optimum design of the new FRP sandwich floor panel by using Finite Element (FE) and Genetic Algorithm (GA) method. The panel consisted of GFRP skin and Phenolic core. The problem formulation and solution are described in detail.

James B. Min, et al [10] investigated the use of sandwich panels with solidface sheet and metal foam core for air plane rotor blades. The face sheets and metal foam core were made of high strength and high toughness aerospace grade precipitation hardened 17-4PH SS. Stress analysis results showed that under combined impact, rotation and pressure loading condition the sandwich panel resulted in lower von Mises stresses in face sheets compared to other blade conditions. The max displacement was also found lower than the solid Ti-6Al-4V blade.

Important and that panels is a non-polluting material. Sandwiches-panels on the equipment which also corresponds to all norms operating in territory of the Russian federation. Manufacturing of sandwich panels using bolted connections discussed in [11].

Detailed guidelines and numerical formulations to be used are given in [15]. The numerical formulations are given for various conditions like for studying Linear Elastic Response, Ultimate Strength, Fatigue analysis, vibration analysis, impact analysis. With small changes in constants the relations proved good for the current case study. This is proved though the comparison of analytical results and the results predicted though FEA. Calculations are given in the next chapter. It may be noted that MathCAD 14.0 was used to do the calculations.

Krzysztof Magnucki, et al [1] investigated pure bending and axial compression of all steel sandwich panels. The relationship between the applied bending moment and the deflection of the beam under four-point bending is discussed. The analytical and numerical (FEM) calculations as well as experimental results are described and compared. Moreover, for the axial compression, the elastic global buckling problem of the analyzed beams is presented

Z. Aboura, et al [2] proposed an analytical model for assesing the behaviour of corrugated cardboard. Computed homogeneous of linear corrugated cardboard behavior is made use in this model. Experimental method for validating the same is described. A parametric study is conducted studying the effect of geometrical parameters on in-plane elastic properties. FE method used to study the relevance of homogenization method. FE modeling is

done in two ways: 1. As 3D solid model, 2. As Shell Model. Shell model is easier and quicker to solve but the results in both the cases were comparable.

L. St-Pierre, et al [3] carried out FE simulations on corrugated sandwich panels with top and bottom facing present and only top facing present. 3-Point bending was simulated. 3-Point bending tests were performed experimentally also. Experimental and analytical predictions are in good agreement with each other. During experimentation, it was found that sandwich beams with front-and-back faces present collapsed by indentation whereas structures without a back face collapsed by Brazier plastic buckling.

A lightweight sandwich panel construction with a thin-walled core provides a system to use undervalued lingo-cellulosic based materials for production of structural and non-structural panels is investigated by Christopher Ray Voth [5]. Analysis of the core design is performed to investigate the process that can be utilized for engineering design of future sandwich panel cores. Small-diameter Ponderosa Pine wood-strands were utilized in fabrication of a lightweight sandwich panel that has a specific bending stiffness (D , lb-in²/in) 88% stiffer than commercial OSB. The sandwich panels designed within this study utilize 60% less wood-strands and resin by weight compared to OSB panels of equivalent thickness. A case study was performed on the wood-strand sandwich panels to determine their potential in structural flooring as an alternative for OSB. The sandwich panel can support a 40 psf live load and a 20 psf dead load without exceeding IBC (2006) deflection limits. Mathematical formulation is presented. The theoretical results are verified experimentally by conducting various tests like 3-point bending tests, Flatwise compression tests, and core shear flexure tests. Various applications are studied practically like for flooring applications, book shelf etc.

Haydn N. G. Wadley, et al [6] investigated the use of sandwich structures for underwater applications. During the investigations, it was found that significant reductions in the fluid structure interaction regulated transfer of impulse occur when sandwich panels with thin (light) front faces are impulsively loaded in water. Combined experimental and computational simulation approach has been used to investigate this phenomenon during the compression of honeycomb core sandwich panels. Square cell honeycomb panels with a core relative density of 5% have been fabricated from 304 stainless steel.

Amit Kumar Jha [7], in his thesis investigated the use of sandwich panels for aerospace applications. In his thesis, free vibration analysis of aluminum honeycomb structure performed. FEA Software ANSYS used to obtain the natural frequencies. Eight noded isoparametric shell element is used for FEA (ANSYS). A detailed parameter study has been carried out of a simply supported sandwich panel by increasing the core depth as a percentage of its total thickness, while maintaining a constant mass. Experimental setup used to validate the simulation results. The results showed that the fundamental natural frequency of the sandwich panel is 1.4 times more than that of a plain panel. The difference increases with increase in modes. Increase in thickness of core increases natural frequency and increase is more at higher modes. Increase in density of the core decreases the natural frequency of the sandwich plate. Theoretically natural frequency is inversely proportional to density of the sandwich plate hence density increase natural frequency decreases.

An experimental and computational study of the bending response of steel sandwich panels with corrugated cores in both transverse and longitudinal loading orientations has been performed by L. Valdevit, et al [8]. Panel designs were chosen on the basis of failure mechanism maps, constructed using analytic models for failure initiation it was found that the analytic models provide accurate predictions when failure initiation is controlled by yielding. However, discrepancies arise when failure initiation is governed by other

mechanisms. One difficulty is related to the sensitivity of the buckling loads to the rotational constraints of the nodes, as well as to fabrication imperfections. The second relates to the compressive stresses beneath the loading pattern. To address these deficiencies, existing models for core failure have been expanded. The new results have been validated by experimental measurements and finite element simulations.

Shawn R. McCullough [12] investigated the behavior of LASER welded corrugated sandwich panels stiffened with concrete. The panel tested is a corrugated sandwich panel with top and bottom steel facing separated by steel corrugation. Welding is done at both crests and troughs. Concrete layer is placed on the top of the sheet utilizing shear connector to ensure composite action. Structural behavior of these composites was evaluated. Investigations showed a high increase in stiffness of the sandwich panel when concrete is used. When 1.5” thick concrete is used, there is a 140% increase in stiffness recorded while 240% increase in stiffness is observed when 2.5” thick concrete is used. Main applications of these sandwich panels include emergency bridge repair, building floors, fire walls etc. Beam Theory (for narrow panels) and classical theory of orthotropic plates used for analyzing the plates. Experimental testing used to prove the results. Results are verified for both 3-Point and 4-Point loading.

3. FABRICATION OF CORRUGATED PANELS

The method of fabrication of panels consists of two stainless steel sheets and in between a corrugated core is inserted and these panels are joined by means of spot welding which is as shown in the Figure - 1 below. The geometrical specification of the panel is also shown in the Figure.-2

Figure – 1 Panel structure of R₂ Shape

Figure – 2 Nomenclature of the corrugated panel

Design of Experiments by Taguchi method

Taguchi method is a method that chooses the most suitable combination of the levels of controllable factors by using S/N tables and orthogonal arrays against the factor that form the variation in product and process. Hence, it tries to reduce the variation in product and process. Hence, it tries to reduce the variation in product and process. Hence, it tries to reduce the variation in product and process to least. Taguchi uses statistical performance measure which is known as S/N ration that takes both medium and variation into consideration. Design optimization problems in automotive industries are usually complex in formulation of objective functions and problems have uncontrollable variations in parameters. To overcome this issue, Taguchi method is adopted in solving the shape design optimization. The architecture of the proposed approach is given in Figure – 3.

In this study, determination of shape of the panel and core geometry is most important parameters in design of corrugated panels. For the analysis purpose the material selected for face sheet is Stainless steel AISI – 304 and for core two different materials are considered one is Mild steel and other one is parent material i.e Stainless steel. As said above for the analysis three types of panel shapes are considered in the present case, in which two are rectangular panels and one is square panel. The two rectangular panels are of same size but lay of core is in transverse and longitudinal direction along the width as shown in the Figure – 4. Along with these parameters, the other three are the corrugated shape, height of the core and face sheet gauge. The design parameters and their levels are shown in the Table – 1.

Figure – 3 Design Optimization approach

Table – 1 Parametric investigation

S.No	Parameter	Level – 1	Level – 2	Level – 3
1	Material Combination (MC):	SSMS- Face sheet x Core	SSSS- Face sheet x Core	
2	core shape (CS)	R-Rectangular core	V-Shape core	
3	Face sheet thickness (FS)	20 gauge	18 gauge	
4	Core height (CH)	18mm	20mm	24mm
5	Panel Shape (PS)	R1- Rectangular panel of length 500(L) X250(W)	R2-Rectangular panel of length 250(L) X 500(W)	SQ-Square panel of 350mm X 350mm

Material combination, core shape, Face sheet thickness, Core height and Panel shape are considered as design parameters to determine their effect on the Flexural Modulus of the Sandwich panel.

A total of 36 experiments based on Taguchi L36 mixed level orthogonal array were carried out with mixed combinations of the input parameters which are shown in Table -2, from this table the material combinations presented are “SSMS” & “SSSS” in which the first two letters indicates face plates and the next two letters indicate core material (i.e., SSMS indicates- Stainless Steel face plates & Mild steel core material; Similarly, SSSS indicates both core and face plates are made of stainless steel). The second parameter considered is core shape which is Rectangular (R) and Dove-tail(V) corrugated sheets as the core materials for the panel. Gauge of the sheets were also considered as one of the parameter for the analysis. Two gauges were considered i.e. 20 and 18. The other important parameters for minimizing the volume fraction are the core height (20, 24 & 28 mm) and the panel shapes are rectangular & square as explained in the previous session.

The Considered models using Taguchi method (L36) were analyzed by three point bending test using ANSYS Work Bench. In the present analysis the model was developed by considering the spot-welding of face-plate and core.

Table -2: Orthogonal Array of L36 of Taguchi

Model No	Material Combination	Core Shape	Face sheet Gauge	Core Height	Panel shape	Model No	Material Combination	Core Shape	Face sheet Gauge	Core height	Panel shape
1	SSMS	R	20	20	R1	19	SSSS	R	18	20	R2
2	SSMS	R	20	24	R2	20	SSSS	R	18	24	SQ
3	SSMS	R	20	28	SQ	21	SSSS	R	18	28	R1
4	SSMS	R	20	20	R1	22	SSSS	R	18	20	R2
5	SSMS	R	20	24	R2	23	SSSS	R	18	24	SQ
6	SSMS	R	20	28	SQ	24	SSSS	R	18	28	R1
7	SSMS	R	18	20	R1	25	SSSS	R	20	20	SQ
8	SSMS	R	18	24	R2	26	SSSS	R	20	24	R1
9	SSMS	R	18	28	SQ	27	SSSS	R	20	28	R2
10	SSMS	V	20	20	R1	28	SSSS	V	18	20	SQ
11	SSMS	V	20	24	R2	29	SSSS	V	18	24	R1
12	SSMS	V	20	28	SQ	30	SSSS	V	18	28	R2
13	SSMS	V	18	20	R2	31	SSSS	V	20	20	SQ
14	SSMS	V	18	24	SQ	32	SSSS	V	20	24	R1
15	SSMS	V	18	28	R1	33	SSSS	V	20	28	R2
16	SSMS	V	18	20	R2	34	SSSS	V	20	20	SQ
17	SSMS	V	18	24	SQ	35	SSSS	V	20	24	R1
18	SSMS	V	18	28	R1	36	SSSS	V	20	28	R2

A series of models as mentioned in table -2 were analyzed to determine the Flexural rigidity of the panel by considering the mode of failures as Shear, Von-mises stresses and the lateral deflection by Three Point Bending Test. A constant load of 5000N was applied in determination of the above stresses and deflections. The goal of this analysis work was to investigate the effects of Flexural Rigidity and observed deflection of the panel. In Taguchi there are three categories of quality characteristics in the analysis of S/N ratio are lower the better, Higher the better and Nominal the better. Regardless of the category of the quality characteristic, process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The category the –lower-the-better was used to calculate the S/N ratio for all the observed parameters.

4. RESULTS:

The measured values of the Flexural-Rigidity and deflection for the models corresponding to all the experimental runs are given Table -3.

Signal to Noise ratio: Analysis of influence of each control factor on the flexural rigidity and deflection has been performed is so called Signal to Noise ratio response Table.

Response table of S/N ratio for Von-mises, Shear stresses and Deflections are shown in the Tables -4, 5, 6 respectively. The influence of each control factor can be clearly presented with the response graphs. The slope of the line which connects between the levels can clearly show the power of the influence of each control factor.

Table -3: Experimental Results

Model No	Von Mises Stress (MPa)	Shear Stress (Mpa)	Deformation (mm)	Model No	Von Mises Stress (MPa)	Shear Stress (MPa)	Deformation (mm)
1	137.71	75.328	0.3332	19	15.769	8.741	0.017551
2	105.69	59.709	0.22843	20	94.987	53.981	0.19447
3	137.68	77.523	0.45744	21	96.627	47.949	0.50398
4	137.71	75.328	0.33324	22	15.769	8.741	0.017551
5	105.69	59.709	0.22843	23	94.987	53.981	0.19447
6	137.68	77.523	0.45744	24	96.627	47.949	0.50398
7	137.29	75.096	0.33028	25	73.927	38.167	0.10313
8	25.394	14.164	0.094139	26	233.99	132.31	0.69529
9	68.8	38.264	0.23172	27	73.383	41.97	0.19827
10	113.26	59.884	0.39075	28	49.818	26.358	0.14367
11	49.454	27.431	0.13016	29	105.45	54.884	0.37319
12	60.302	34.228	0.14519	30	23.958	13.742	0.19047
13	22.075	11.944	0.09827	31	89.815	50.304	0.17262
14	43.272	22.846	0.13129	32	116.67	60.287	0.46334
15	89.842	46.983	0.33685	33	40.6	22.81	0.12289
16	22.075	11.944	0.09827	34	89.815	50.304	0.17262
17	43.272	22.846	0.13129	35	116.67	60.287	0.46334
18	89.842	46.983	0.33685	36	40.6	22.81	0.12289

Table-4:Response table for S/N Ratios (Smaller is better) for Von-mises stresses

Level	Material Combination	Core Shape	Face sheet Gauge	Core Height	Panel shape
1	-36.91	-38.24	-39.27	-35.98	-41.82
2	-36.65	-35.32	-34.29	-37.99	-31.30
3				-36.37	-37.23
Delta	0.25	2.93	4.98	2.01	10.53
Rank	5	3	2	4	1

Table-5:Response table for S/N Ratios (Smaller is better) for Shear stresses

Level	Material Combination	Core Shape	Face sheet Gauge	Core Height	Panel shape
1	-31.68	-33.05	-34.10	-30.63	-36.31
2	-31.37	-29.99	-28.05	-32.74	-26.26
3				-31.20	-32.00
Delta	0.32	3.06	5.15	2.11	10.05
Rank	5	3	2	4	1

Table-6: Response table for S/N Ratios (Smaller is better) for Deformation

Level	Material Combination	Core Shape	Face sheet Gauge	Core Height	Panel shape
1	13.490	13.687	12.408	16.805	7.642
2	14.350	14.153	15.433	12.665	19.124
3				12.291	14.995
Delta	0.860	0.466	3.025	4.514	11.483
Rank	4	5	3	2	1

Figure – 4: Main Effects plot for S-N Ratio for Von-Misses stress

Figure – 5: Main Effects plot for S-N Ratio for Shear stress

**A- Material Combination
B- Core Shape
C- Face sheet Gauge
D- Core Height
E- Panel shape**

Figure – 6: Main Effects plot for S-N Ratio for Deformation

5. DISCUSSION

It is seen from the response Tables and according to the Rank for each control factor that the panel shape had the strongest influence on Von-misses stresses and Shear Stresses followed by face sheet gauge, Core Shape, Core height and least influence on Material combination. Similarly from the response table of Deformation and according to the Rank for each control factor that the panel shape had the strongest influence on Deformation followed by Core height, face sheet gauge, Material combination and least influence on Core Shape.

From the Main effects plot for S/N ratio for Von-Misses Stresses Fig.4 the Von-Misses Stresses appears to be linear increasing function for Material Combination(A), Core Shape(B) and Face sheet Gauge (C) and variation in the levels for core height (D) and panel shape (E). Thus in order to reduce the von-Misses stresses under particular loading condition the following levels has to be considered(Refer Table - 7).

Table - 7: Selected levels for the fabrication of the corrugated panel

Parameter	Level
A- Material Combination	SSSS-Face and core material as Stainless steel
B- Core Shape	V-Dove-Tail corrugated sheet
C- Face sheet Gauge	18 gauge stainless steel
D- Core Height	20mm
E- Panel shape	Rectangular

It is observed that the core height is being considered as 20mm since as height increases the possibility of sliding failure of the panel may occur and V-Dove-Tail corrugated sheet is considered from the analysis instead of rectangular section since the rectangular section is taking the direct load while the Dove-Tail is taking resultant load. From the Main effects plot for S/N ratio for Deformation Fig.6, the Deflection appears to be linear similar to Von-Misses stresses as explained above.

5.1 Experimental Results: The corrugated Panel is fabricated for the above optimum levels of the considered parameters and tested for Three-Point Bending. In the Analysis the maximum load applied is 5kN and the results were drawn which are shown in Figure 7 & 8. From the experiments, the corrugated panel has endured a maximum load of 15kN. Hence the model is recommended up to 10kN. Fig 9 and Fig 10 shows the experimental testing of fabricated corrugated sandwich under three point bending test.

Figure -7: FEA Results for Max shear stress

Figure - 8: FEA Results for Max Von-mises stress

Figure - 9: Experimental test of three point bending test

Figure - 10: Tested panel in three point bending test.

6. CONCLUSIONS

This Study discussed an application of the Taguchi-Method for Dimensional optimization of corrugated panel using performance measures of Three-Point Bending Test. From this Research conclusions could be reached with a fair amount of confidence. From the Taguchi Analysis the optimum levels decided is not modeled in L36 models. Hence for validation of the above said result is carried out. And it is observed that the maximum shear stress, Von-Misses stresses and deflections are 11.882Mpa,22.161 Mpa,0.09mm respectively. From the experiments the maximum load endured by the panel is three times more than the considered load. Finally for minimum stress induced and deflection, core and face plate are made of stainless steel of gauge 18, core height as 20mm, core shape as Dove-tailed corrugated sheet and the panel shape is rectangular with corrugations along the width is considered for fabrication.

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