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Original Article

Optimal Combination of Liner, Fibre and Shell Thicknesses in Carbon Fibre-Overwrapped Composite Pressure Vessels

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Abstract *- The purpose of this study was to determine the optimal combination of shell, fibre and liner of a composite pressure vessel resistant to bursting strength. The optimal range of fibre and shell thicknesses was predetermined to achieve an improved sustainable composite pressure vessel. Through the design of the experiment adopted in the Minitab software, the Box-Behnken was used in the optimization of fibre and shell held as dependent variables while the liner was held as the independent variable. Therefore, using the Minitab software version 2016 allowed the combination of these variables to yield an optimal composite on two profiles considered in this study. The generated results of the combination of the ultimate factors value yield on two profiles an optimal design with a probability of 95% for it to be normal. These factors the liner, fibre and shell, have been found to have different influences on the hoop stress response and to each other. With the objective of the study achieved, optimization of the first profile was found with a liner of 4.8 mm, a fibre of 0.5 mm and shell thickness of 2.7 mm. For the second profile, optimization was recorded at a liner of 9.5 mm, 2.1 mm of fibre and 5.5 mm of shell thickness. In brief, the determination of these optimal parameters was obtained with a strength improvement of 4% and 33% weight reduction comparatively to the whole metallic pressure vessel. In addition, hoop stress values of 123.43 MPa and 123.84 MPa, Von Mises values of 178.56 MPa and 178.7 MPa and Tresca values of 179.48 MPa and 179.62 MPa were obtained on Profile 1 and 2, respectively. These values led to the consideration of profile 1 as the most optimal of the two profiles studied.*

Keywords *- Composite pressure vessels, Thickness, Hoop stresses, Optimization, Fibre and Shell.*

1. Introduction

Pressure vessels have been used as storage systems for numerous applications. In the industrial sector, for instance, usage of these vessels has been applied in air cylinders or nitrogen pressure systems [1]. It is also applied in the automotive industry, where the replacement of fuel oil with compressed natural gas has been used for the reduction of emissions and improvement of the quality of air. The success of these applications relies on the storage technology where the capacity to withstand bursting failure due to an unsupported pressure has been found as a limitation [2].

Hence, the idea of incorporating a material as a fibre shell overwrapping a metallic liner to form a composite pressure vessel was thought to reduce failures occurring on a conventional metallic pressure vessel. Despite the structures being tolerant to damage of metallic vessels under a predetermined specific pressure range, the exposure to unsupported loads (pressure) requires an increase in structural thickness, ultimately leading to an increase in weight. The optimization of composite pressure vessel design gave the ability to withstand bursting failure as each structural constituent (liner, fibre and shell) was chosen at their ultimate magnitude. The purpose of this study was, therefore to the development of a composite overwrapped pressure vessel by the combination of the best optimal structural options of the constituent. Carbon fibre overwrapping the liner gave it the ability to withstand the load and avoid structural failure caused by unsupported pressure. Hence making it more damage tolerant and more efficient than a completely metallic pressure vessel without additional weight to carry the mentioned load.

2. Materials and Methods

Previous studies have been carried out separately on the effects of fibre and shell thicknesses on the bursting strength of carbon fibre-overwrapped composite pressure vessels [3],[4]. However, the two studies did not evaluate the thickness effects of the combined liner, fibre and shell on bursting strength with the aim of establishing the optimal combination, despite this phenomenon being the common practice in the industry. Therefore, this study seeks to use the data generated by the two studies above to determine the optimal combination of these configuration parameters. The optimization process of a composite pressure vessel was done using the Minitab software version 2016 to identify the best option in fibre and shell thickness, which, upon the combination, would yield an optimal design on profiles 1 and 2. The design of the experiment adopted in the Minitab software was Box-Behnken, whereby the fibre and shell were held as dependent variables while the liner was held as the independent variable. Therefore, the use of the Minitab software version 2016 allowed the combination of these variables to yield an optimal composite [5], [6].

Table 1. Fibre thickness of profile 1 [3]

Orientation (Degree)	Profile 1					
	Positive			Negative		
	Part No	Stainless steel liner (mm)	Fibre (mm)	Part No	Stainless steel liner (mm)	Fibre (mm)
55	1	3.35	0.1594	8	3.35	0.1594
55	2	3.908	0.2169	9	3.908	0.2169
55	3	4.467	0.2834	10	4.467	0.2834
55	4	5.025	0.3586	11	5.025	0.3586
55	5	5.583	0.4426	12	5.583	0.4426
55	6	6.142	0.5357	13	6.142	0.5357
55	7	6.7	0.6288	14	6.7	0.6288

Table 2. Fibre thickness of profile 2 [3]

Orientation (Degree)	Profile 2					
	Positive			Negative		
	Part No	Stainless steel liner (mm)	Fibre (mm)	Part No	Stainless steel liner (mm)	Fibre (mm)
55	15	6.7	0.6375	22	6.7	0.6375
55	16	7.817	0.8677	23	7.817	0.8676
55	17	8.933	1.1	24	8.933	1.1
55	18	10.05	1.4	25	10.05	1.4
55	19	11.167	1.8	26	11.167	1.8
55	20	12.283	2.1	27	12.283	2.1
55	21	13.4	2.3	28	13.4	2.33

Table 3. Shell thickness of profile 1 [4]

Orientation (Degree)	Profile 1					
	Symmetrical			Asymmetrical		
	Part No	Stainless steel liner (mm)	Shell (mm)	Part No	Stainless steel liner (mm)	Shell (mm)
55	1	3.35	10	8	3.35	9.3
55	2	3.908	5	9	3.908	4.6
55	3	4.467	3.3	10	4.467	3.1
55	4	5.025	2.5	11	5.025	2.3
55	5	5.583	2	12	5.583	1.8
55	6	6.142	1.6	13	6.142	1.5
55	7	6.7	0.7	14	6.7	0.6

Table 4. Shell thickness of profile 2 [4]

Orientation (Degree)	Profile 2					
	Symmetrical			Asymmetrical		
	Part No	Stainless steel liner (mm)	Shell (mm)	Part No	Stainless steel liner (mm)	Shell (mm)
55	15	6.7	20.1	22	6.7	18.6
55	16	7.817	10	23	7.817	9.3
55	17	8.933	6.6	24	8.933	6.1
55	18	10.05	4.9	25	10.05	4.6
55	19	11.167	3.9	26	11.167	3.6
55	20	12.283	3.3	27	12.283	3
55	21	13.4	1	28	13.4	0.9

The analytical methodology adopted in the process of fibre thickness determination led to the findings of the allowable fibre size of this study. Under the lease susceptibility failure theorem referred to the Tsai Wu criteria, this required dimension used in the optimal generation of pressure vessel sustainability to resist bursting failure, upon determination of the range detrimental to the integrity of the container.

Therefore, as both profiles considered in this study had generated fibre thickness in the positive and negative direction, the theorem mentioned earlier was also used to determine the sustainable direction of the optimal angle used. Hence, using the failure theorem gave the range of sustainability and guided the direction to adopt as Tables 1 and 2 have depicted in a positive and negative orientation.

The Shell thickness of profiles 1 and 2 used in the optimization are depicted for this study in Tables 3 and 4. These shell thicknesses have been generated in symmetrical and asymmetrical patterns of lamination. Therefore, have a better insight into the effects of the chosen patterns (symmetrical and asymmetrical) over the shell thickness and determine the suitable choice for optimization.

2.1. Sustainable Ply Thickness Range

The Tsai Wu failure criteria depicting the first ply failure of the determined ply thickness have been used to generate the range of plies with the required sustainability to develop an optimal design process.

From Figure 1, it is apparent that both profiles exhibited corresponding criteria on parts profiles 1 to 7. Based upon the Tsai Wu failure criteria, the range of ply thickness exposing the vessel to less susceptibility to failure and to be used for the optimization was observed in part profiles 5 and 6. These correspond to ply thickness of 0.4426 mm to 0.5357 mm on the first and 1.8 mm to 2.1 mm on the second.

These thicknesses of the two profiles have been chosen because of failure criteria closer to stability on Tsai Wu parameter 1 (1 -Stability- 3 ; 3 -Prompt to failure- 6; 6 -failure- more) were recorded on this part profile composite pressure vessel [5].

The 7th part profile was not considered an optimal option because its corresponding liner thickness reached the maximum variation gap (between 3.35-6.7 mm and 6.7-13.4 mm).

2.2. Sustainable Shell Thickness Range Determination

The predetermined shell thickness was used with the internal pressure that produced axial and hoop stress to determine the most optimal design of composite made of liner and lamination shell. Therefore, with strength as the driving factor of this study, the hoop stresses (Table 5) were taken to have an influential effect on the governing of the bursting failure of the vessel.

From Table 5, it is evident that despite the double factor between profiles, the hoop stress generated for the different models of symmetrical and asymmetrical patterns exhibited similarity in values with a degree of discrepancy of 1 %. The threshold hoop stress generated from the stainless-steel vessel of thickness 6.7 mm for the first profile and 13.4 mm for the second profile with the same internal pressure of 8 MPa was found unchanged for the two profiles with a value of 119.4 MPa. The sustainable range of shell thickness used in the optimization was depicted in Figures 2 and 3, with the comparison made between symmetrical and asymmetrical patterns on the two industrial profiles based upon the results of hoop stress of the respective allowable shell thicknesses. It was clearly apparent that the asymmetrical hoop stress generated on both profiles gave better results than the symmetrical hoop stress generated on both profiles with an average of 2% more, making this pattern the most desirable option for a vessel overwrapped with a shell layer. With the intention of finding the shell thickness that was most optimal for a reliable composite pressure vessel, the same hoop stress exhibited in Figures 2 and 3 was used.

These hoop stresses were generated from the respective allowable shell thickness, making the second and third optimal thickness on both profiles, with 3.1 and 2.3 mm for the first profile and 6.1 and 4.6 mm for the second. This was because they represented an improvement from the limit threshold (119.4 MPa) of a whole stainless-steel vessel required to handle the same internal pressure as the composite.

Table 5. Hoop stress of profiles 1 and 2 [4]

	Profile 1		**Profile 2**	
Parts	**Symmetry (MPa)**	**Asymmetrical (MPa)**	**Symmetry (MPa)**	**Asymmetrical (MPa)**
1	95.340	98.564	95.121	98.564
2	117.32	121.00	117.31	120.52
3	123.31	125.52	123.32	125.52
4	121.36	123.61	121.91	123.61
5	116.72	118.86	117.24	118.85
6	111.60	112.58	111.12	112.59
7	111.79	112.81	113.85	114.38

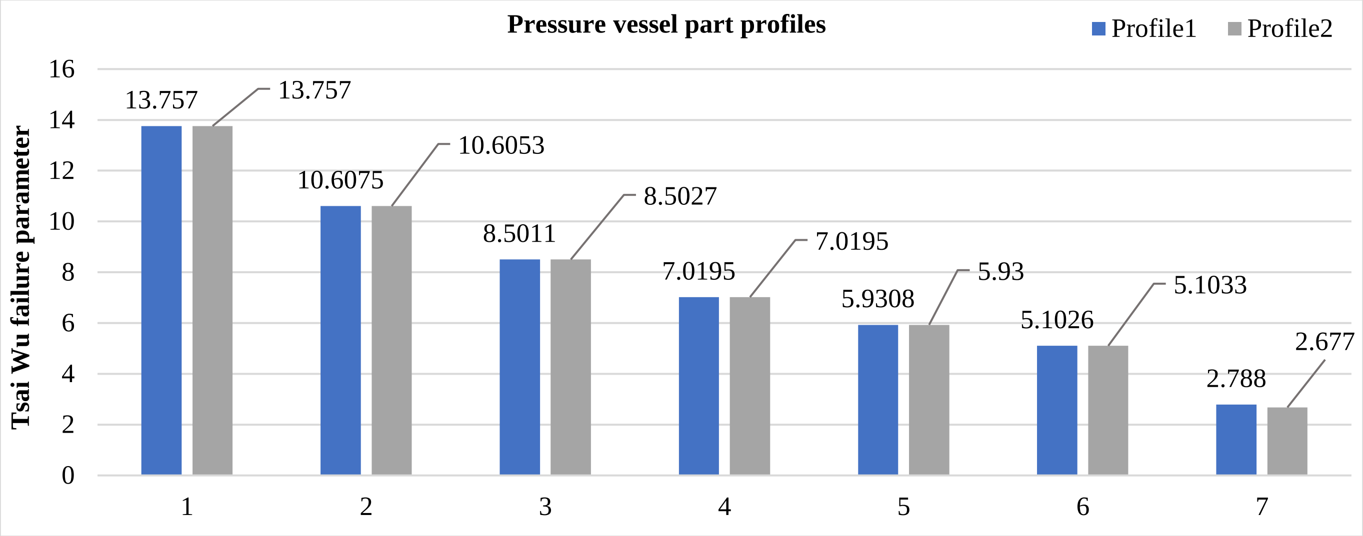


Fig. 1 Sustainable range of ply thickness [3]

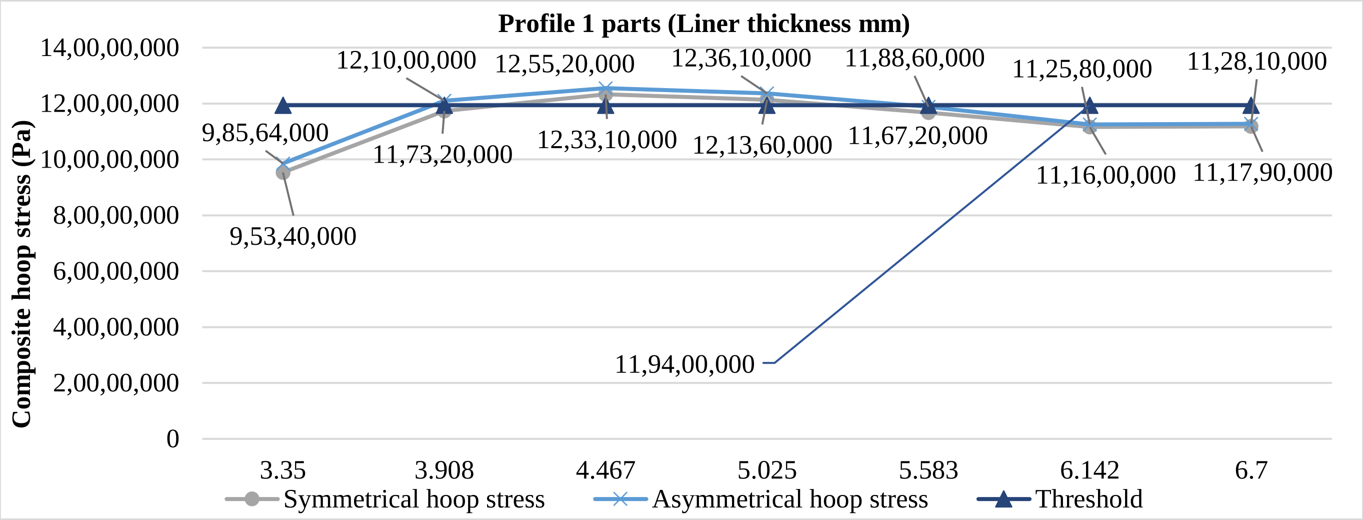


Fig. 2 Shell thickness range of profile1

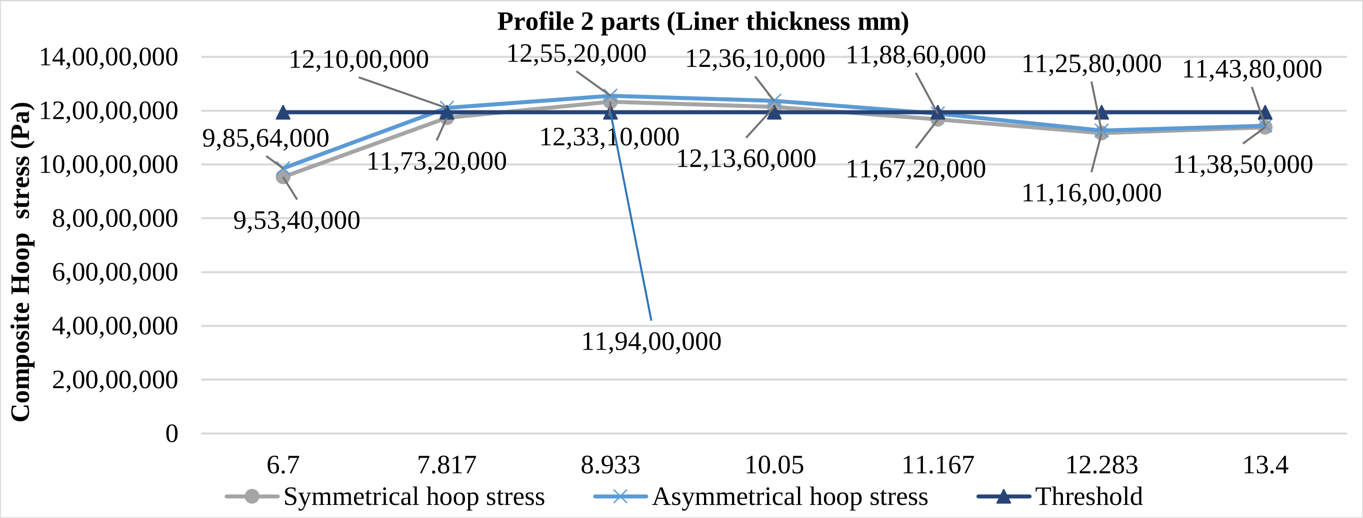


Fig. 3 Shell thickness range of profile 2 [4]

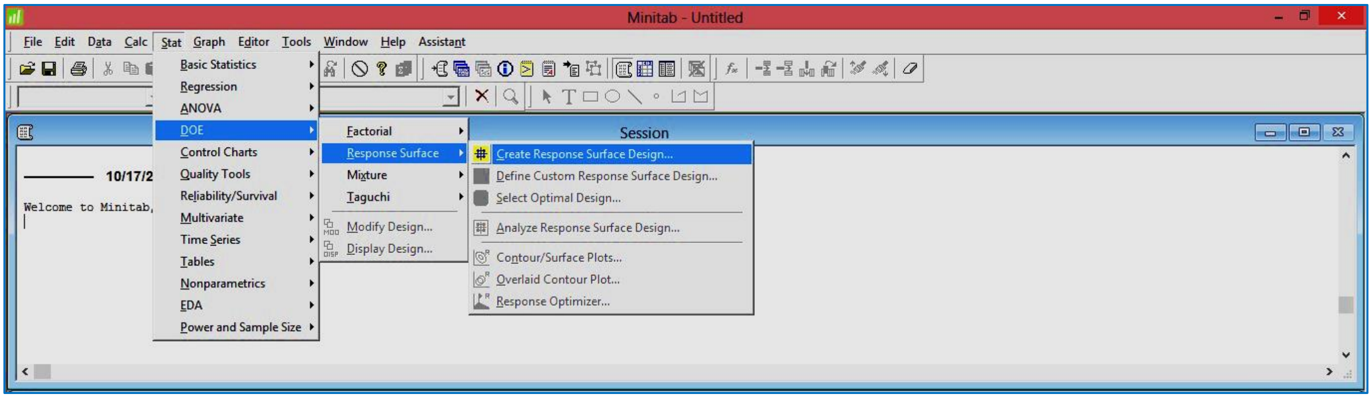
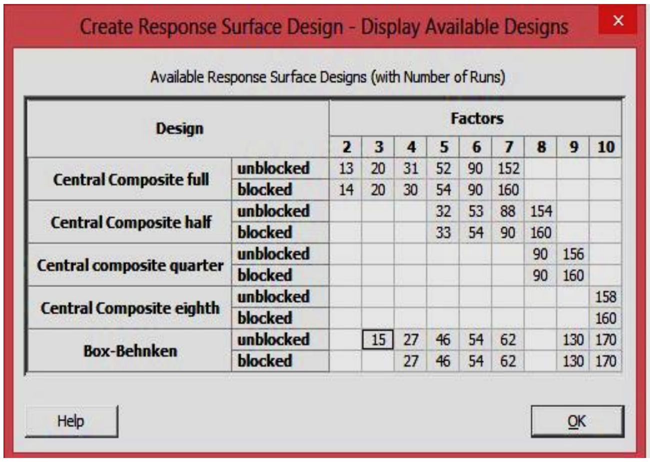


Fig. 4 Creation of response surface design steps



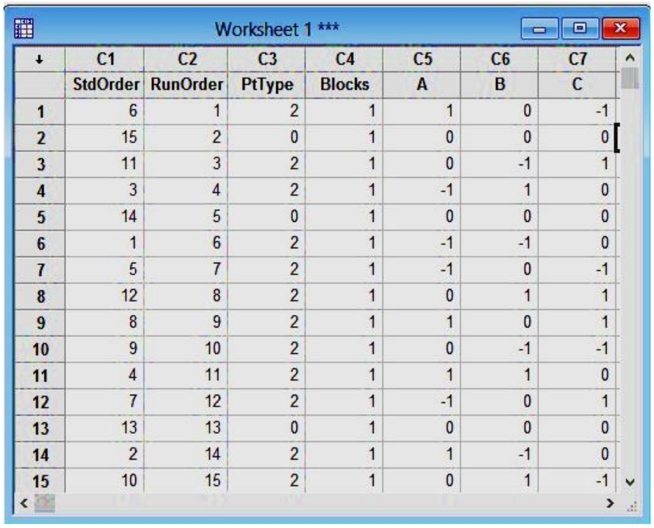
Available Response Surface Designs (with Number of Runs)

Design		Factors								
		2	3	4	5	6	7	8	9	10
Central Composite full	unblocked	13	20	31	52	90	152			
	blocked	14	20	30	54	90	160			
Central Composite half	unblocked				32	53	88	154		
	blocked				33	54	90	160		
Central composite quarter	unblocked							90	156	
	blocked							90	160	
Central Composite eighth	unblocked									158
	blocked									160
Box-Behnken	unblocked		15	27	46	54	62		130	170
	blocked			27	46	54	62		130	170

Fig. 5 Box Behnken design

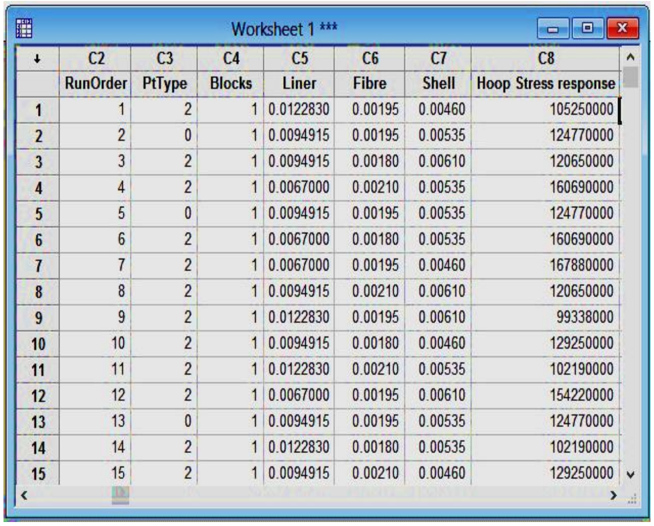
↓	C1	C2	C3	C4	C5	C6	C7	C8
	StdOrder	RunOrder	PtType	Blocks	Liner	Fibre	Shell	Hoop Stress response
1	6	1	2	1	0.006142	0.0004892	0.0023	105250000
2	15	2	0	1	0.004746	0.0004892	0.0027	124480000
3	11	3	2	1	0.004746	0.0004426	0.0031	120120000
4	3	4	2	1	0.003350	0.0005357	0.0027	160230000
5	14	5	0	1	0.004746	0.0004892	0.0027	124480000
6	1	6	2	1	0.003350	0.0004426	0.0027	160230000
7	5	7	2	1	0.003350	0.0004892	0.0023	167880000
8	12	8	2	1	0.004746	0.0005357	0.0031	120120000
9	8	9	2	1	0.006142	0.0004892	0.0031	98966000
10	9	10	2	1	0.004746	0.0004426	0.0023	129250000
11	4	11	2	1	0.006142	0.0005357	0.0027	101990000
12	7	12	2	1	0.003350	0.0004892	0.0031	153410000
13	13	13	0	1	0.004746	0.0004892	0.0027	124480000
14	2	14	2	1	0.006142	0.0004426	0.0027	101990000
15	10	15	2	1	0.004746	0.0005357	0.0023	129250000

Fig. 7 Profile 1 optimal factorial pattern



↓	C1	C2	C3	C4	C5	C6	C7
	StdOrder	RunOrder	PtType	Blocks	A	B	C
1	6	1	2	1	1	0	-1
2	15	2	0	1	0	0	0
3	11	3	2	1	0	-1	1
4	3	4	2	1	-1	1	0
5	14	5	0	1	0	0	0
6	1	6	2	1	-1	-1	0
7	5	7	2	1	-1	0	-1
8	12	8	2	1	0	1	1
9	8	9	2	1	1	0	1
10	9	10	2	1	0	-1	-1
11	4	11	2	1	1	1	0
12	7	12	2	1	-1	0	1
13	13	13	0	1	0	0	0
14	2	14	2	1	1	-1	0
15	10	15	2	1	0	1	-1

Fig. 6 Optimization pattern



↓	C2	C3	C4	C5	C6	C7	C8
	RunOrder	PtType	Blocks	Liner	Fibre	Shell	Hoop Stress response
1	1	2	1	0.0122830	0.00195	0.00460	105250000
2	2	0	1	0.0094915	0.00195	0.00535	124770000
3	3	2	1	0.0094915	0.00180	0.00610	120650000
4	4	2	1	0.0067000	0.00210	0.00535	160690000
5	5	0	1	0.0094915	0.00195	0.00535	124770000
6	6	2	1	0.0067000	0.00180	0.00535	160690000
7	7	2	1	0.0067000	0.00195	0.00460	167880000
8	8	2	1	0.0094915	0.00210	0.00610	120650000
9	9	2	1	0.0122830	0.00195	0.00610	99338000
10	10	2	1	0.0094915	0.00180	0.00460	129250000
11	11	2	1	0.0122830	0.00210	0.00535	102190000
12	12	2	1	0.0067000	0.00195	0.00610	154220000
13	13	0	1	0.0094915	0.00195	0.00535	124770000
14	14	2	1	0.0122830	0.00180	0.00535	102190000
15	15	2	1	0.0094915	0.00210	0.00460	129250000

Fig. 8 Profile 2 optimal factorial pattern

2.3. Optimal Combination of Factor

With the reference method being analytical, the data generated as analytical results were the ones used in the Minitab software for optimization analysis. The option of response surface exhibited in Figure 4 gave the option of Design of Experiment (DOE) to be adopted in the analysis.

The Box Behnken experimental design was selected from the software statistical and data analysis function, as seen in Figure 5, with three factors and three minimum, average, and maximum levels. With this setting, Minitab performed 15 simulations from the response surface creation function, which for this design was as seen in Figure 6, representing -

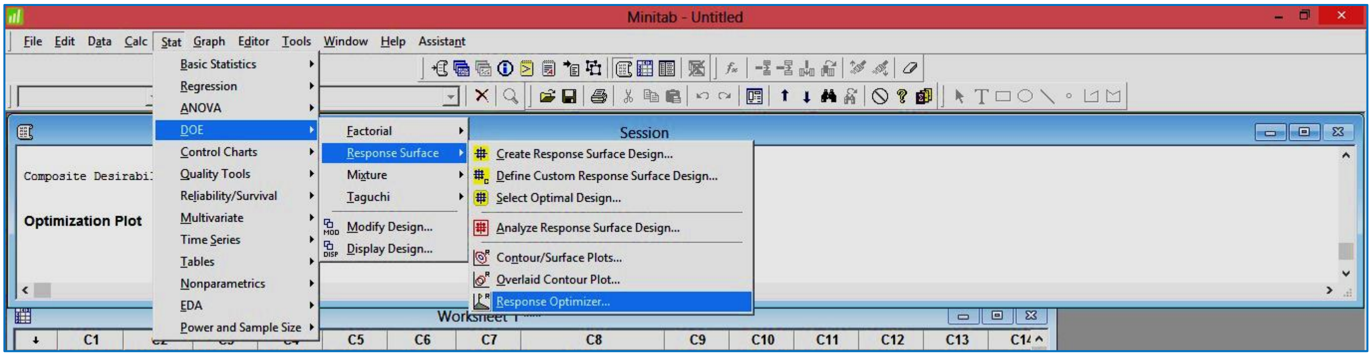
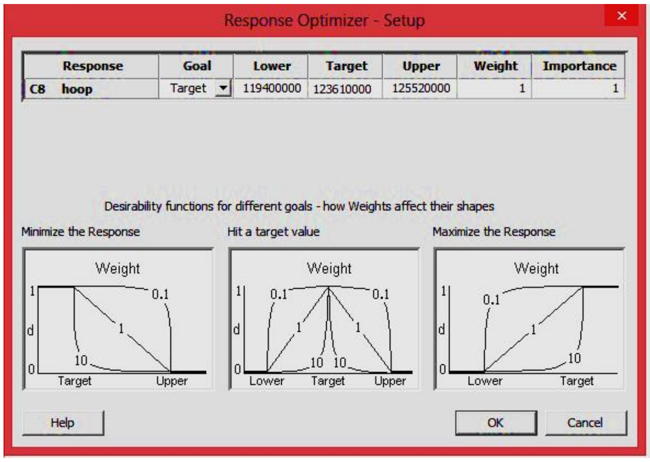


Fig. 9 Response optimization process



Response	Goal	Lower	Target	Upper	Weight	Importance
C8 hoop	Target	119400000	123610000	125520000	1	1

Fig. 10 Target response setting

- a generated optimization pattern to be replaced by the minimum, average and maximum factors of the liner, fibre, and shell. The connotation of this figure was as (-1) being the minimum, (0) the average and (1) the maximum.

Columns A, B and C were therefore replaced with factors considered in this experimental design: the liner, the fibre and the shell thickness, which affect the hoop stress as shown in Figures 7 and 8. The maximum and minimum replacement factor values were taken from the determined range.

On the other hand, the liner was considered for both profiles at maximum and minimum, respectively, at the first and last increment model variation. With this replacement set, the hoop stress response column was generated from the 3 levels factorial design.

The response optimizer function in Minitab software, shown in Figure 9, was, therefore, used after creating and analyzing the response to exhibit the effect of factors on the response with set targets of hoop stress in a composite pressure vessel, as shown in Figure 10. The optimal solution occurred when the maximum desirability of liner, fibre and shell were obtained and the optimization values of strength were generated.

For more confirmation of the optimal result, the ANOVA (Analysis of variance) software was used, whereby the importance of each factor on the optimization process was determined with the significant level denoted by p. This parameter was used for exhibiting the influence of each factor or independent groups (fibre and shell thickness) on the response. These verification processes were associated with the normality test to have hypotheses tests under the basic statistic option. Further details on the statistical analysis are presented in Appendix A.

3. Results and Discussion

3.1. Outline

This section presents the results and discussions on the design of an optimal composite pressure vessel through the optimal combination of stainless-steel liner and carbon fibre shell as influential factors to the integrity of the structure. The effect of these influential factors and results generated from the study are represented in graphs and tables in this section to emphasize the sustainability of the composite structural integrity with the aim of resisting bursting failure. The ultimate result of fibre and shell thickness yielded a combined optimal design for which strength improvement was obtained.

3.2. Optimization of the liner, fibre, and shell thickness for optimal strength

The optimization concept of Minitab regressed in a probabilistic manner, all the unnecessary influential terms of the response leaving only the optimal factor based upon the target set-up. Through Analysis of Variance (ANOVA), the significant effect of factors used as input parameters was determined, with the p-value emphasizing the importance brought to the response. This was based on the hypothesis that input factors have a strong influence when the respective p-value is greater than 0.005.

3.2.1. Effect of Influential Factors on Hoop Stress Response

With strength aimed for optimization, emphasis was made on the factor influencing the response, taken for this study as the structural hoop stress of the composite pressure vessel. This level of influence on the hoop stress characterized by the P value can be observed in Figures 11 to 13, with shell p values of 0.009 on profile 1 and 0.014 on profile 2. The most influential factor in the response was recorded to be on the fibre, with a p-value of 0.896 on profile 1 and 0.905 on profile 2. The less influential parameter was recorded on the liner, which was also the study's independent variable with a p-value of 0.001 over the hoop stress response on both profiles.

The results exhibited on fibre influence over the hoop stress were partly due to its interactive influence over the shell itself being part of its constituent. From Figure 12, it was apparent that fibre influence was also more expressed in Profile 2 than in Profile 1 due to the dimension's double increment between a profile that was also influential to the response value.

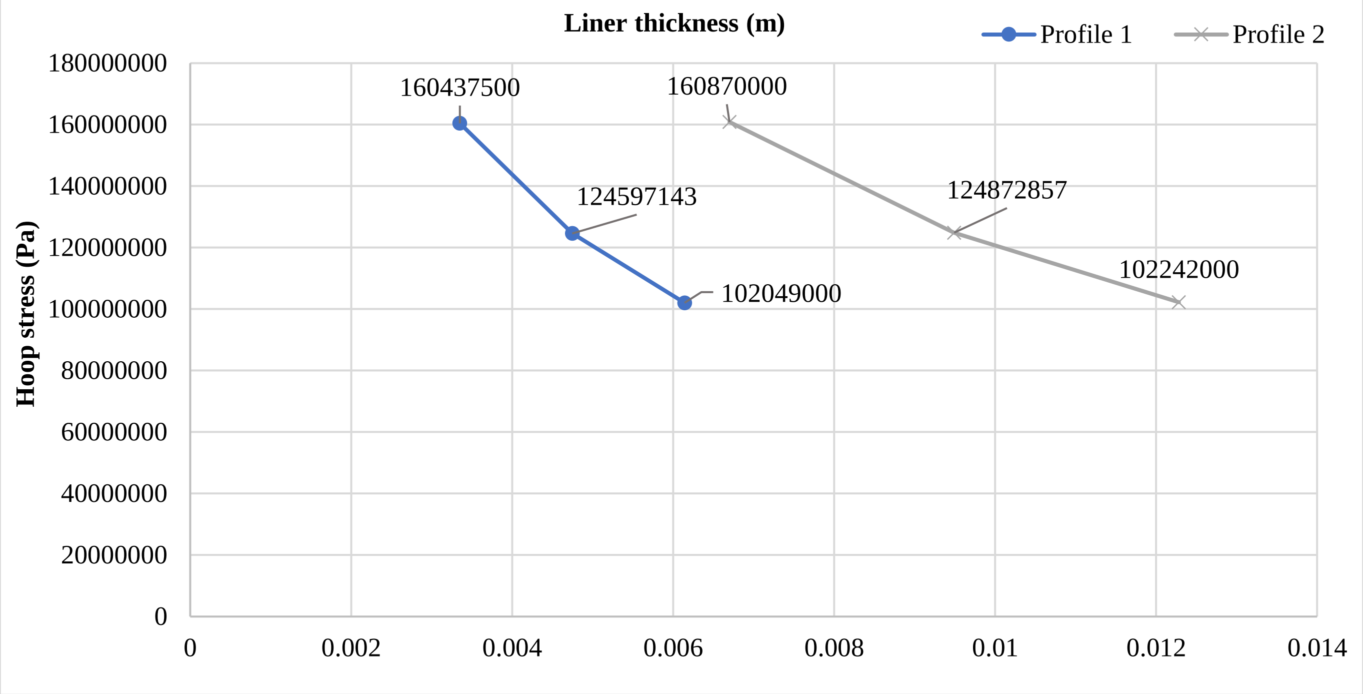


Fig. 11 Profile 1 and 2 Liner influence representation on hoop stress response

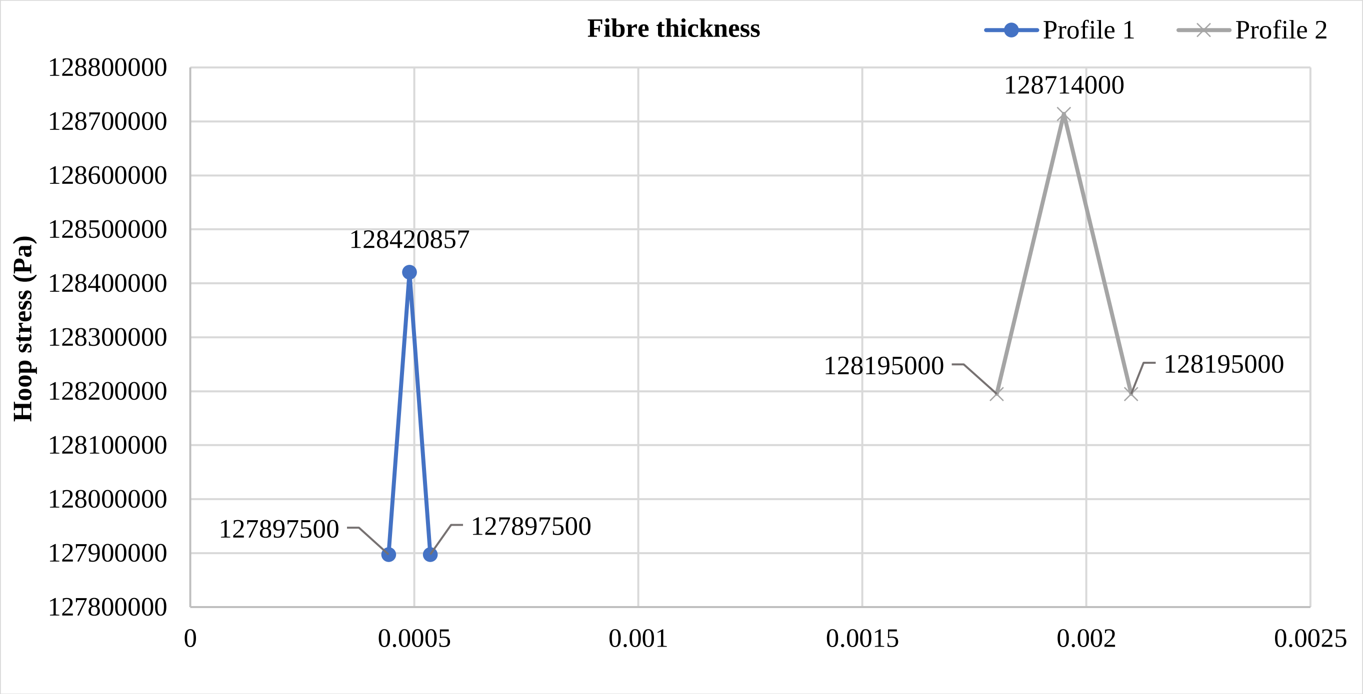


Fig. 12 Profile 1 and 2 fibre influence representation on hoop stress response

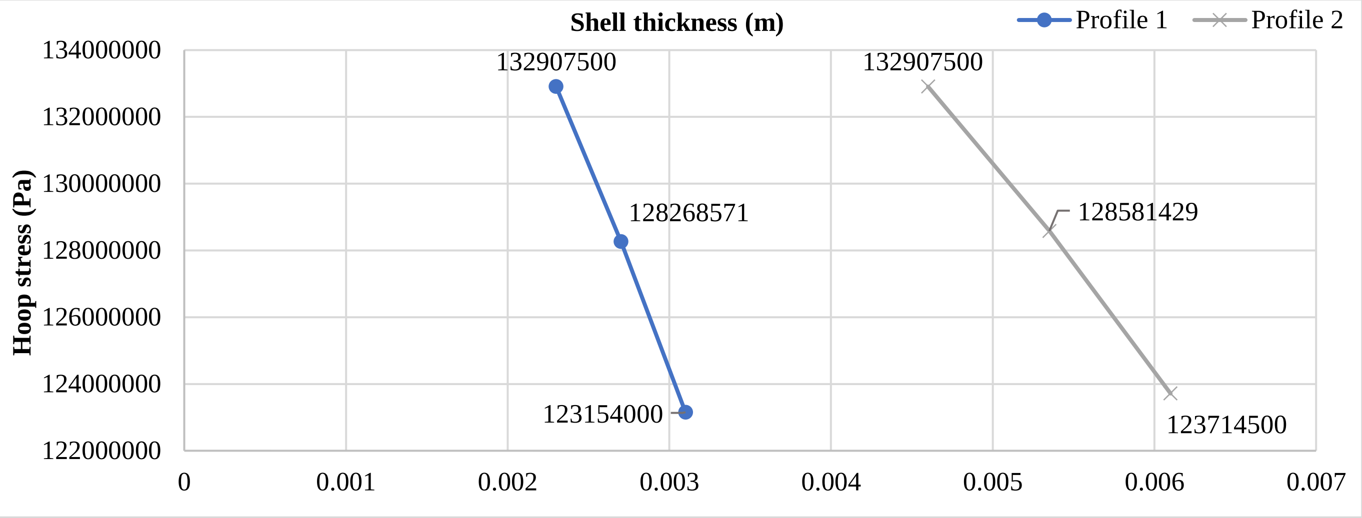


Fig. 13 Profile 1 and 2 shell influence representation on hoop stress response

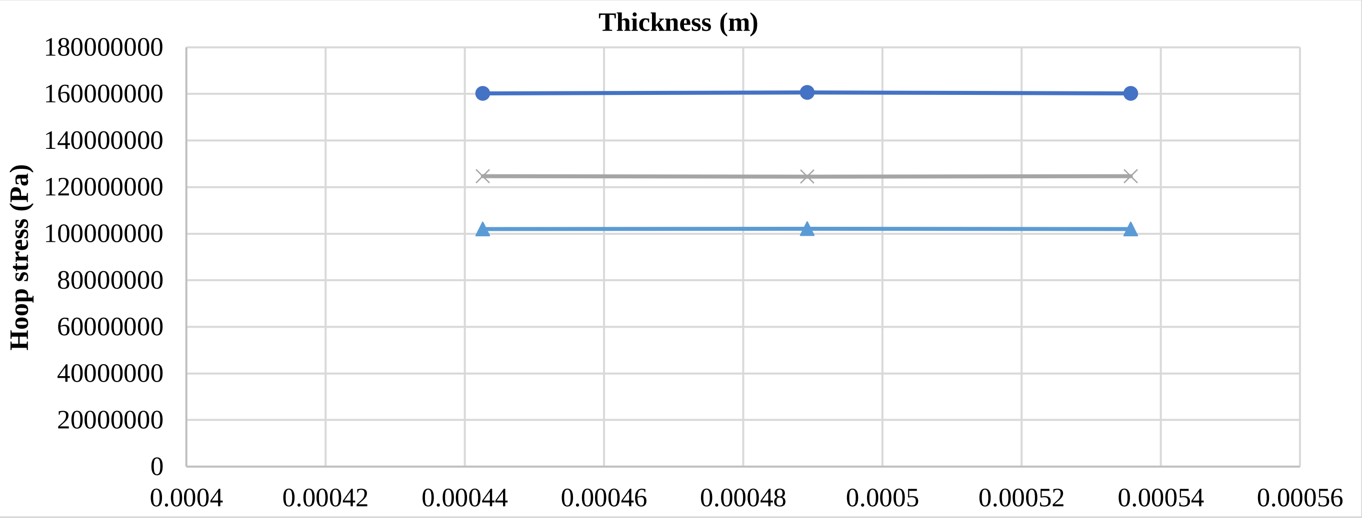


Fig. 14 Profile1 liner and fibre interaction

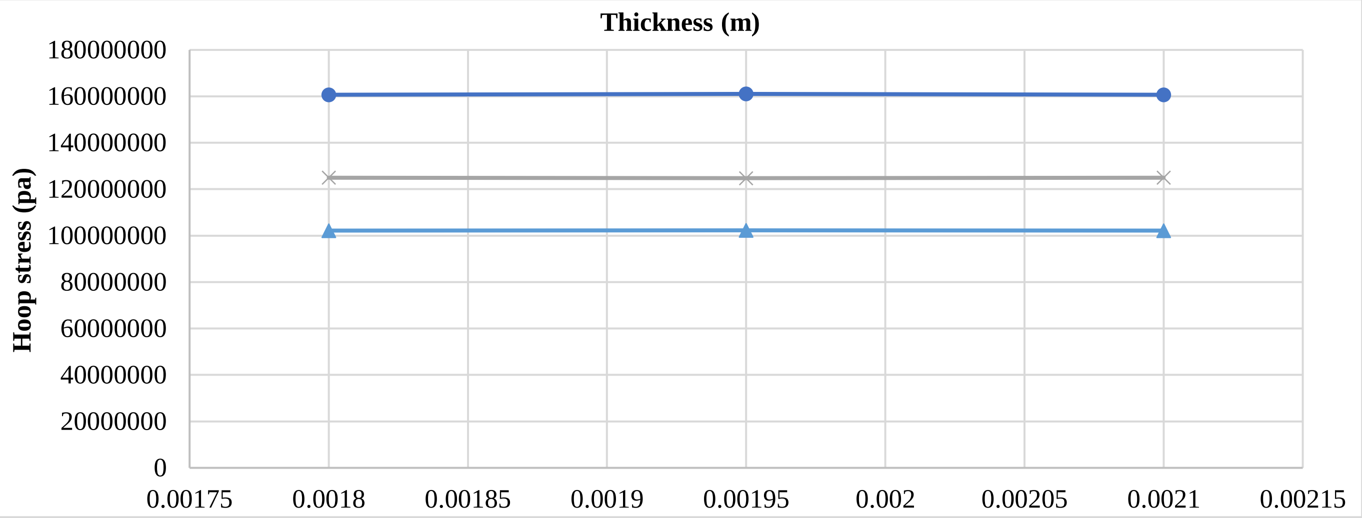


Fig. 15 Profile 2 liner and fibre interaction

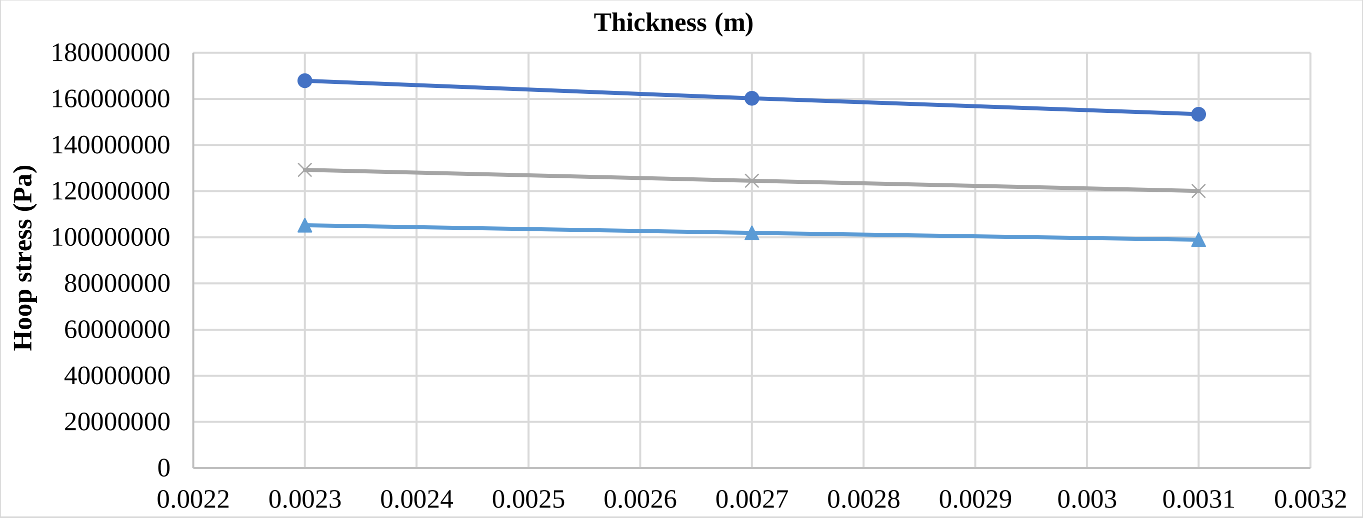


Fig. 16 Profile1 liner and shell interaction

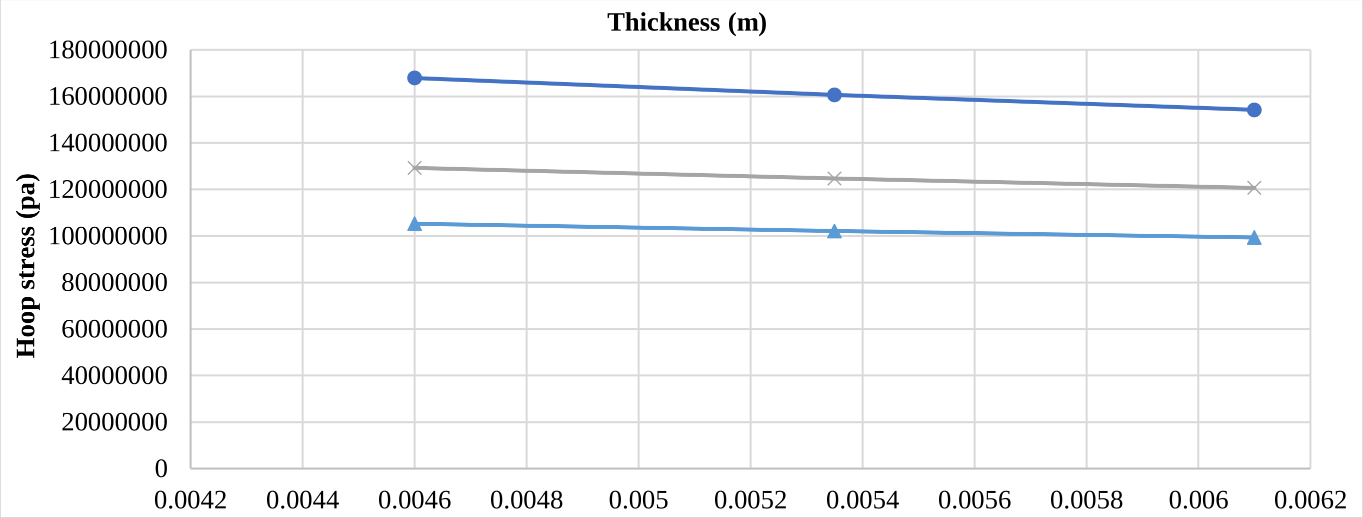


Fig. 17 Profile 2 liner and shell interaction

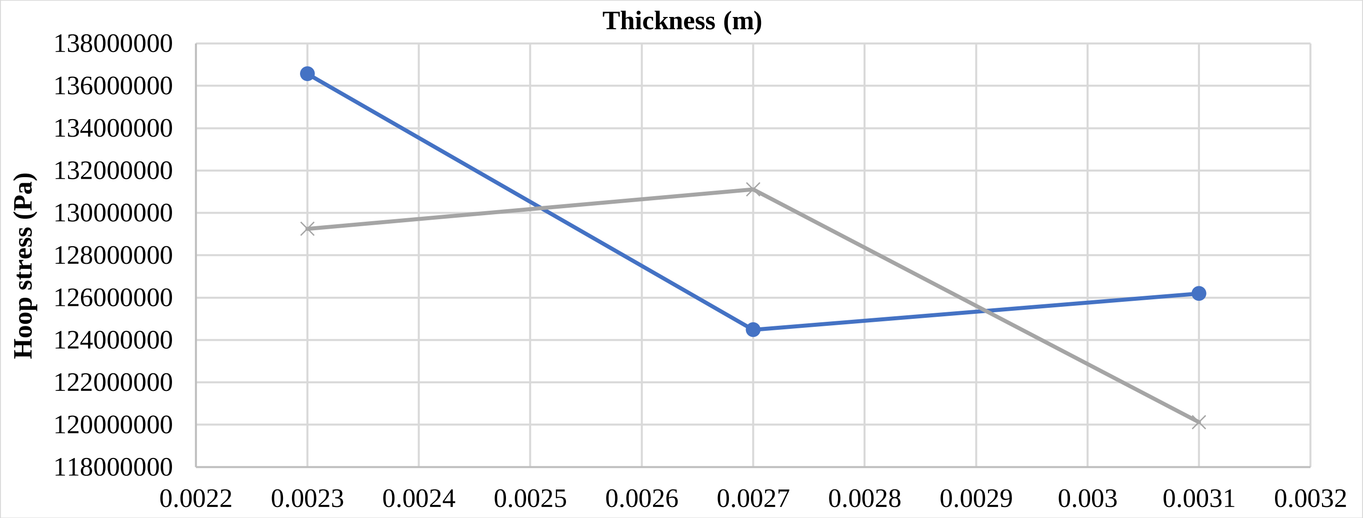


Fig. 18 Profile 1 fibre and shell interaction

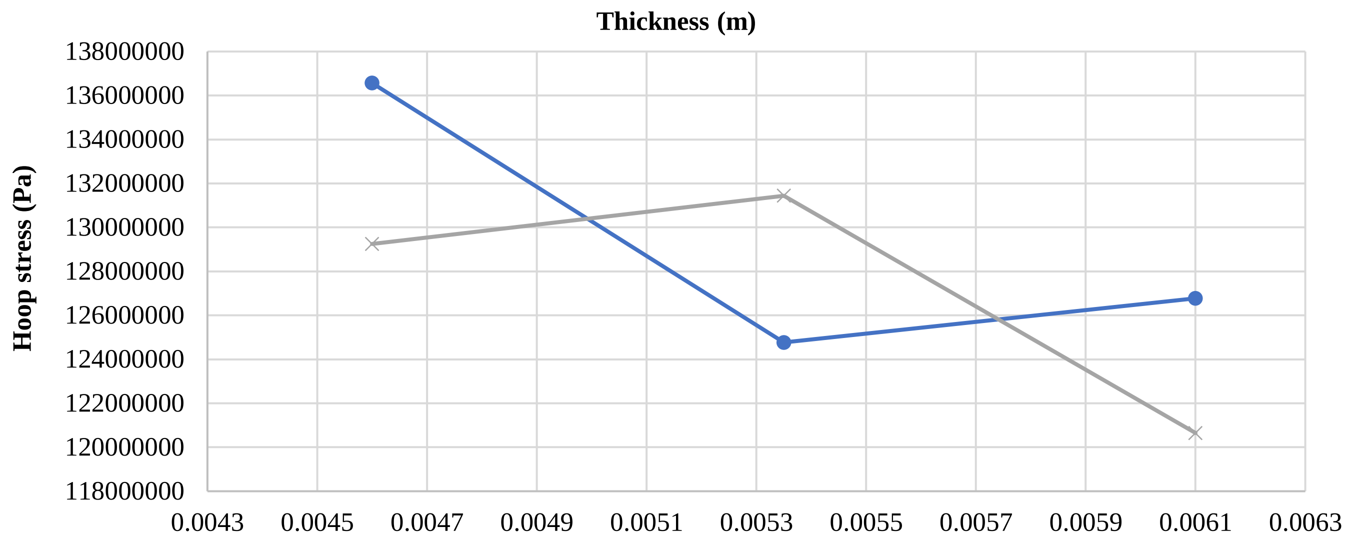
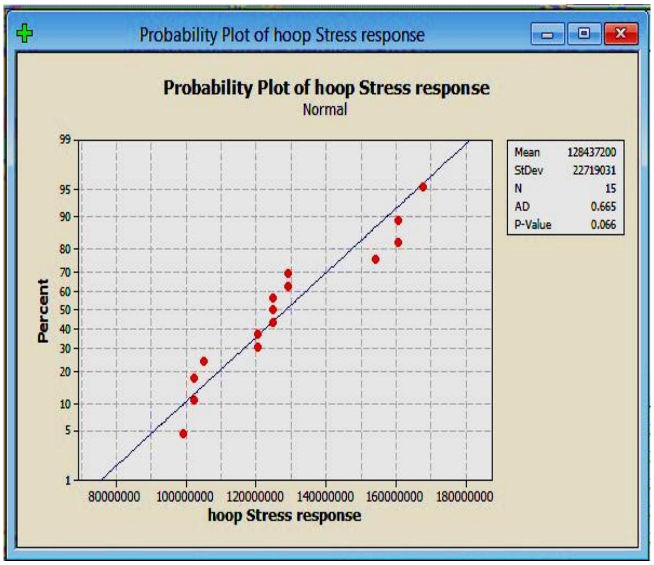


Fig. 19 Profile 2 fibre and shell interaction

From Figures 14 to 19, it was observed that there was a great interaction influence of fibre over the other factors of the response with a p level of 1. It was also evident that there was less interaction experienced between the liner and the shell, explaining the little influence these factors have on the hoop stress response. (Refer to Appendix A for further insight into the interaction between factors).

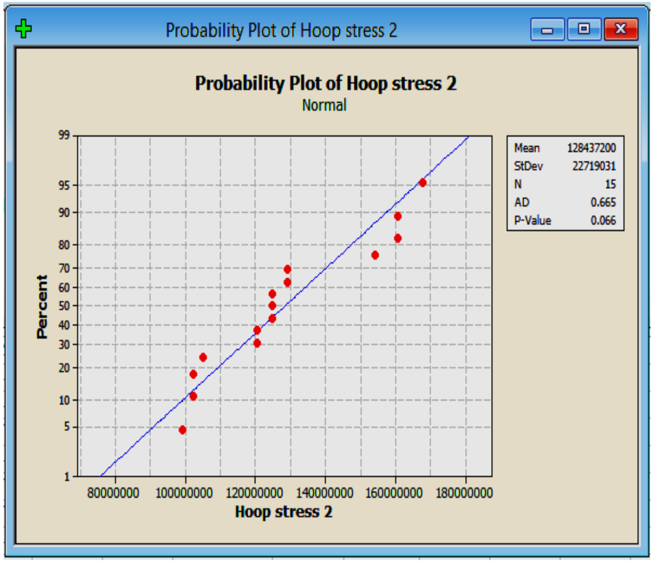
3.2.2. Probability Normality Test

With the intent of statistical demonstration of normality on an optimal design, a probability test was done on the response interaction with its factors on both profiles 1 and 2, as observed in Figures 20 and 21. It was evident that the ANOVA assumptions were met on the normality test as each response was equally distributed along the line, as shown in both Figures 20 and 21.



Mean	128437200
StDev	22719031
N	15
AD	0.665
P-Value	0.066

Fig. 20 Normality test of response on profile 1



Mean	128437200
StDev	22719031
N	15
AD	0.665
P-Value	0.066

Fig. 21 Normality test of response on profile 2

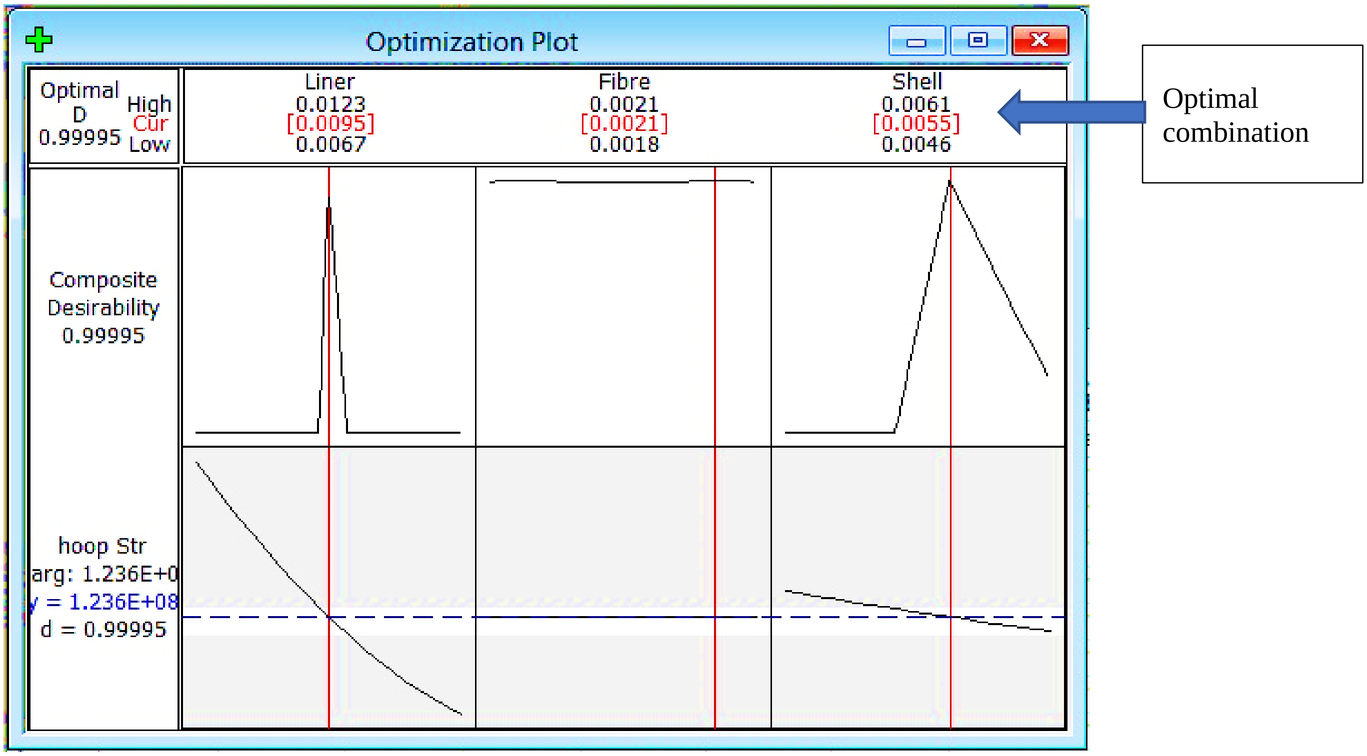
Furthermore, the p-value of 0.066 was greater than 0.005, making the optimization probability of these designs to be greater than 95% on both profiles. These results confirmed the probability of being an optimal design from the generated factors of liner, fibre and shell thickness, influencing the hoop stress response. With this normality test met on both profiles, a reassurance on the designs' optimization was therefore verified.

3.2.3. Optimal Design of Profile 1 and Profile 2

With the purpose of the study designed to improve profiles and generate an ultimate combination of the influential factors to the composite structure, optimization was achieved by analyzing vessel strength with the hoop stress as the response criteria. Therefore, upon application of Minitab response optimizer, achievement of optimization was reached on a liner value of 4.8 mm, fibre value of 0.5 mm and shell thickness value of 2.7 mm, making the desired composite pressure vessel of profile 1, as exhibited in Figure 22. On the second profile, optimization was achieved at a liner value of 9.5 mm, fibre thickness of 2.1 mm and ultimately, a shell thickness of 5.5 mm, as exhibited in Figure 23.

This optimal composite pressure vessel designed for profiles 1 and 2 was ultimately the best combination generated from the model's liner variables, fibre and shell thickness, that were influential to the structural strength of the composite pressure vessel. This occurrence was because optimization was set to the threshold target while maximum hoop stress combined composite constituents through this ultimate limitation. In contrast to the stainless steel, this strength improvement was accounted for with a reduced weight of 4.61 kg, representing a reduction of 33% on the first profile. On the second profile, a weight of 36.88 kg with a reduction of 33% as well, making this incorporation of pressure vessels in the form of composite advantageous to various industrial applications. Therefore, the optimal strengths of the composite pressure vessel aimed for, in this study for profiles 1 and 2, were generated from the ultimate liner, fibre and shell value as displayed in Table 6. It is apparent that the pressure vessel designed as a composite has an improved hoop stress of 4% on profiles 1 and 2, comparatively to the stainless-steel pressure vessel with a sustainable stress of 119.4 MPa.

The elastic strength of these optimal designs beyond which failure would occur is shown in Table 6 using Von Mises and Tresca criteria. With strength on both profiles being similarly close under the same percentage of improvement, the comparison between the two considered profiles was therefore referred to as the weight. Hence, with profiles 1 and 2 being of structural weights of 4.61 kg and 36.88 kg, respectively, it follows that profile 1 was the best option due to its reduced cost of materials.

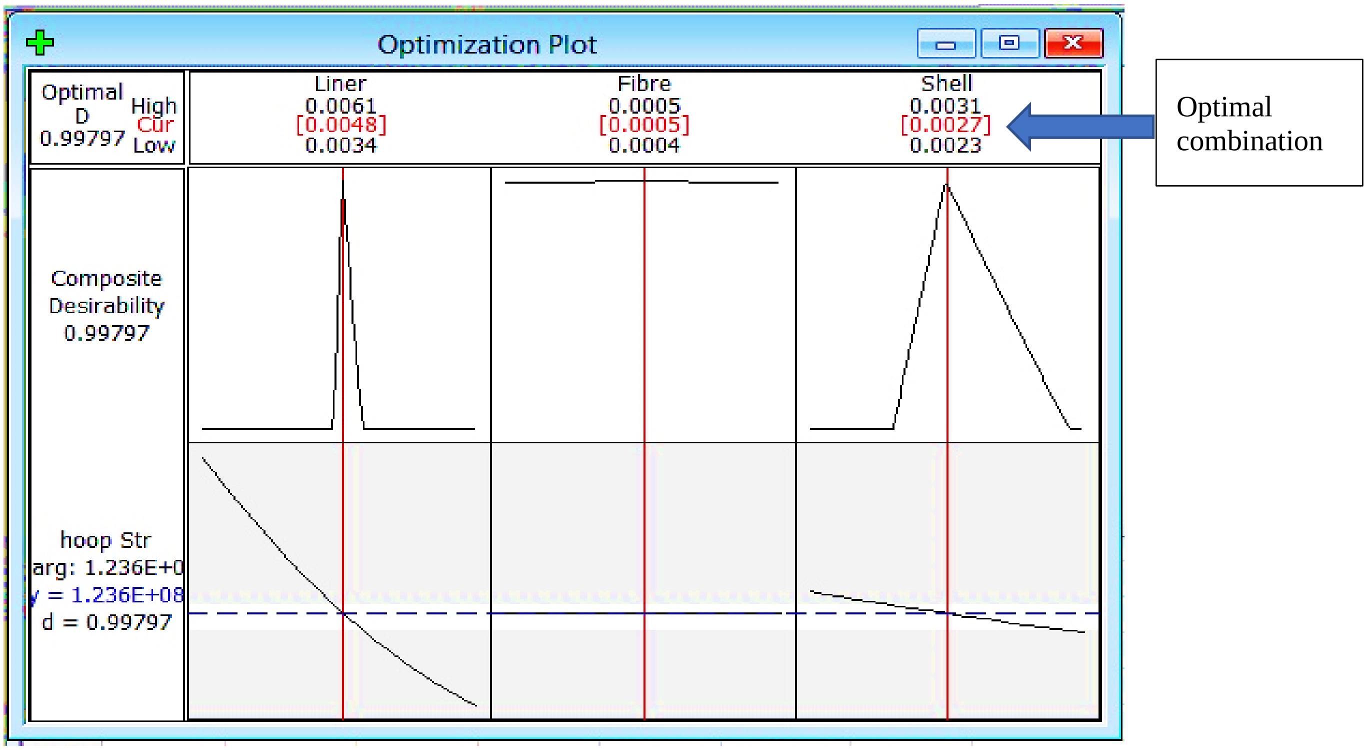


Optimal combination

Fig. 22 Profile 1 optimal plot

Table 6. Optimal strength of composite pressure vessel for profiles 1 and 2

Optimal part profile	Optimal dimensions (mm) Liner, Fibre, Shell	Hoop stress (MPa)	Von Mises (MPa)	Tresca (MPa)
Profile 1	4.8, 0.5, 2.7	123.43	178.56	179.48
Profile 2	9.5, 2.1, 5.5	123.84	178.70	179.62
Similar stainless steel vessel results	-	119.40	172.29	173.18



Optimal combination

Fig. 23 Profile 2 optimal plot

4. Conclusion

The conclusions based on this study's findings are as follows:

1. The combination of the ultimate factors value yielding the optimal design on the two profiles was observed to have a p-value of 0.066, greater than 0.005, entailing a probability of 95% for the design to be normal based upon the hoop stress response.
2. Liner, fibre and shell used as a factor on the optimal process were found to be of a different influence on the response and to each other as fibre was observed to have the least interaction with the liner.
3. The objectives of the study were achieved from the determination of optimal fibre thickness to ultimate shell thickness identification based upon a variation of the liner, which ultimately led to the generation of the optimal design of the two profiles considered in the study. The first was recorded with a liner of 4.8 mm, fibre of 0.5 mm and shell thickness of 2.7 mm. The second design profile was recorded with an optimization liner of 9.5 mm, 2.1 mm of fibre and 5.5 mm of shell thickness.
4. With optimal parameters determined, the optimal designs were, therefore, obtained with the improvement of 4% in strength and 33% in weight reduction, respectively, on profiles 1 and 2.
5. Optimization was obtained with hoop stress values of 123.43 MPa and 123.84 MPa, Von Mises values of 178.56 MPa and 178.7 MPa and Tresca values of 179.48 MPa and 179.62 MPa on Profile 1 and 2, respectively. Therefore, based on these generated results, profile 1 was considered the most optimal of the two profiles studied.

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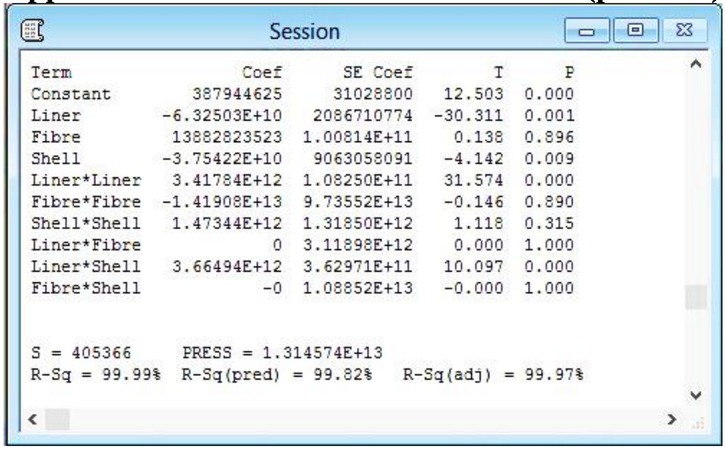
Appendix 1 Constituent interaction factor (profile 1)



```
Term                Coef      SE Coef       T      P
Constant       387944625     31028800  12.503  0.000
Liner       -6.32503E+10   2086710774 -30.311  0.001
Fibre        13882823523  1.00814E+11   0.138  0.896
Shell       -3.75422E+10   9063058091  -4.142  0.009
Liner*Liner  3.41784E+12  1.08250E+11  31.574  0.000
Fibre*Fibre -1.41908E+13  9.73552E+13  -0.146  0.890
Shell*Shell  1.47344E+12  1.31850E+12   1.118  0.315
Liner*Fibre            0  3.11898E+12   0.000  1.000
Liner*Shell  3.66494E+12  3.62971E+11  10.097  0.000
Fibre*Shell           -0  1.08852E+13  -0.000  1.000


S = 405366     PRESS = 1.314574E+13
R-Sq = 99.99%  R-Sq(pred) = 99.82%   R-Sq(adj) = 99.97%
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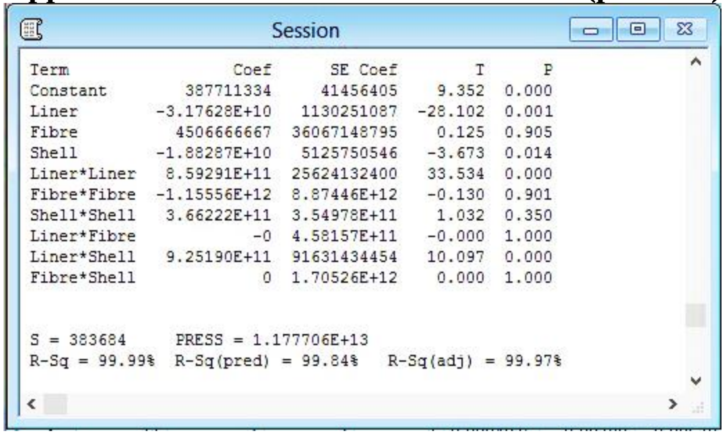
Appendix 2 Constituent interaction factor (profile 2)



```
Term                Coef      SE Coef       T      P
Constant       387711334     41456405   9.352  0.000
Liner       -3.17628E+10   1130251087 -28.102  0.001
Fibre         4506666667  36067148795   0.125  0.905
Shell       -1.88287E+10   5125750546  -3.673  0.014
Liner*Liner  8.59291E+11  25624132400  33.534  0.000
Fibre*Fibre -1.15556E+12  8.87446E+12  -0.130  0.901
Shell*Shell  3.66222E+11  3.54978E+11   1.032  0.350
Liner*Fibre           -0  4.58157E+11  -0.000  1.000
Liner*Shell  9.25190E+11  91631434454  10.097  0.000
Fibre*Shell            0  1.70526E+12   0.000  1.000


S = 383684     PRESS = 1.177706E+13
R-Sq = 99.99%  R-Sq(pred) = 99.84%   R-Sq(adj) = 99.97%
```