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Assessment of Lifeboat Laminate Strength

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ABSTRACT

The objective of this work was to assess the material strength of conventional lifeboat composites and to examine the effect that particular factors have on the strength, using design of experiments methods. The research was a direct response to the growing need for information pertaining to the performance of lifeboats in ice-covered waters. Evaluating the strength of lifeboat laminates was completed through two test programs. The first focused on assessing the tensile strength while the second examined the impact strength.

KEY WORDS: Laminate, Lifeboat, Strength, Experiments.

INTRODUCTION

The research presented in this paper details two sets of laboratory tests that were performed to assess the material strength of lifeboat laminate. The aim of this research was to increase the knowledge base regarding the material properties of lifeboat laminates and to determine critical factors that affect the material performance. The insight gathered from this research can be used to guide regulations or to steer the structural design of an ice capable lifeboat.

DESIGN OF EXPERIMENTS METHODOLOGY

Design of Experiments (DOE) is a technique for developing experimental test plans and analyzing the results that are obtained. The test plans are optimized to reduce the total number of tests required to determine reliable results. DOE is particularly powerful because of its use of statistics to map each effect and to determine which of the examined factors are significant to the measured responses.

Design of Experiments has a number of applications in a broad range of fields. In the case of the experiments being presented in this report, DOE was used for the assessment of material properties and the determination of significant factors relevant to these properties.

There were two laminate properties assessed in this study: tensile

strength and impact strength. The research was conducted via two separate laboratory test programs. The analysis methodology is described by Montgomery (2005).

Tensile Testing

The tensile tests were configured to meet the standards outlined in ASTM: "Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials." The experiments were planned using a five-factor, half-fraction, factorial design with two replicates. Testing was conducted in a calibrated tensile test machine located at Memorial University.

Test Factors

There were five factors considered in the tensile strength assessment: material type, specimen temperature, heat treatment, submergence and pre-stress. A factorial design limits the analysis to two levels for each factor. In this analysis four of the factors were categorical and one was numerical. The numerical factor was specimen temperature.

The upper level of the material type factor was laminate material that came from the hull of an out of use conventional lifeboat. The lower level of this factor refers to laminate that was fabricated to replicate actual lifeboat laminate. A burn test was completed on a piece of actual lifeboat laminate to determine the lay-up schedule that was required for fabrication of the replicated laminate.

The lower and upper level of the specimen temperature was -10°C and 18°C respectively. The upper level was representative of the room temperature of the test site. To obtain the lower level temperature the test specimens were cooled in a freezer room and transferred to the test location in a cooler. The lower temperature level is representative of the mean temperature of the chilled specimens at test time.

Specimens that underwent heat treatment were subjected to repeated temperature changes. The specimen underwent 2 cycles of 24 hours at -20°C and 8 hours at 18°C to simulate typical freeze-thaw cycles that

could be experienced by a lifeboat operating in ice. The number of cycles was limited by the project time frame. The submerged specimens were placed in fresh water at room temperature for seven hours. Pre-stress involved suspending a 5 kg weight from the midpoint of a specimen for 21 hours. Treatment times for submergence and pre-stress, as outlined directly above, were selected such that they fit within the test schedule.

Heat treatment, submergence and pre-stress had an upper level corresponding to “yes” and a lower level corresponding to “no.” The level designations indicated if the treatment was applied or not. For example, a specimen with an upper level of the pre-stress factor was subjected to stress prior to testing.

Each factor was labeled as follows: A – material type, B – temperature, C – heat treatment, D – submergence and E – pre-stress.

Test Results

There were a total of 32 tests conducted to assess the effect of five factors on the tensile strength of laminate. The run description for each of the 32 tests is provided in Table 1.

Table 1: Tensile Test Run Description

Run Number	Material Type	Temperature (°C)	Heat Treatment	Submergence	Pre-Stress
1	Actual Lifeboat	18	Yes	No	Yes
2	Actual Lifeboat	-10	No	No	Yes
3	Replicated Lifeboat	-10	Yes	Yes	No
4	Actual Lifeboat	-10	Yes	Yes	Yes
5	Actual Lifeboat	-10	No	Yes	No
6	Actual Lifeboat	-10	Yes	No	No
7	Actual Lifeboat	18	No	Yes	Yes
8	Actual Lifeboat	18	No	Yes	Yes
9	Replicated Lifeboat	18	No	Yes	No
10	Replicated Lifeboat	18	Yes	Yes	Yes
11	Actual Lifeboat	18	Yes	Yes	No
12	Replicated Lifeboat	18	Yes	No	No
13	Actual Lifeboat	-10	No	Yes	No
14	Actual Lifeboat	18	Yes	No	Yes
15	Replicated Lifeboat	-10	No	No	No
16	Replicated Lifeboat	18	No	No	Yes
17	Actual Lifeboat	-10	No	No	Yes
18	Replicated Lifeboat	-10	No	Yes	Yes
19	Actual Lifeboat	18	No	No	No
20	Replicated Lifeboat	18	Yes	Yes	Yes
21	Replicated Lifeboat	18	No	No	Yes
22	Replicated Lifeboat	-10	Yes	No	Yes
23	Replicated Lifeboat	-10	Yes	Yes	No
24	Actual Lifeboat	18	No	No	No
25	Replicated Lifeboat	-10	No	No	No
26	Replicated Lifeboat	18	Yes	No	No
27	Actual Lifeboat	18	Yes	Yes	No
28	Replicated Lifeboat	18	No	Yes	No
29	Replicated Lifeboat	-10	Yes	No	Yes
30	Actual Lifeboat	-10	Yes	No	No
31	Actual Lifeboat	-10	Yes	Yes	Yes
32	Replicated Lifeboat	-10	No	Yes	Yes

Destructive Impact Panel Testing

The destructive impact panel tests used the ISO standard: “Plastics – Determination of puncture impact behaviour of rigid plastics” as a guideline. Changes to the testing standard were implemented to allow for testing of larger panels, more representative of a lifeboat hull. The modifications affected the test frame, indenter and specimen size. The indenter size was increased from a hemisphere with a diameter of 0.020 m to 0.150 m. The specimens tested were square with dimensions of 0.50 m by 0.50 m.

Testing was completed using a hydraulic ram. The impact experiments were planned and analyzed using a full-factorial four factor design.

Test Factors

The destructive impact panel testing examined 4 different factors at 2 levels each. These factors will be described below along with a discussion to support the selection of each factor and the significance of the levels that were selected. The factors that were examined included temperature at time of impact, laminate thickness, construction method employed and construction materials used.

Temperature

Lifeboats operating in ice-covered waters are exposed to low temperature environments as a result of the surrounding air and water temperatures. A key factor that has been hypothesized to have a significant effect on the strength and impact resistance of a lifeboat hull is the temperature of the material. Analysis of this factor will determine whether temperature has an effect on a fiberglass panel’s ability to resist impact loads. The experiment evaluated the response of impacts on panels at 6°C and 16°C. These temperatures represent cold-water temperature and temperate air temperature respectively.

In an effort to ensure the lowest possible testing temperature was attained, the panels that were tested at low temperature were stored at -20°C until they were tested. At test time the chilled panels were removed from the cold room and fixed to the test frame for immediate testing.

Laminate Thickness

The laminate was tested at 10 mm (approximately 3/8 inch) and 16 mm (approximately 1/2 inch). The laminates of different thickness are similar in layup schedule, employing both chopped strand mat (CSM) and woven roving (WR). The quantity of fiberglass layers required to achieve the correct laminate thickness was different for the 10 mm and 16 mm panels.

Construction Method

The experiment examined two different construction methods in an effort to determine if modern techniques had a significant effect on the strength of the panels that were tested. This factor was tested as a categorical factor.

The first method of construction tested was the traditional hand lay-up technique in which the layers of glass are applied to the mould, wet out and then consolidated together to reduce the chance of de-lamination between layers and to reduce the number of void spaces in the laminate (shown in Figure 1). This technique results in a laminate that is strong, but typically heavy. An additional drawback to this method is that because the laminates are constructed and left to cure in an open mould, there is significant exposure to toxic chemicals and fumes. This has recently been identified as a significant health and safety risk.

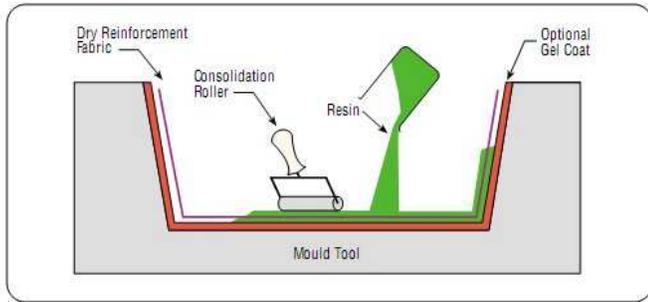


Figure 1 - Hand Layup Method

The second method of construction tested was the vacuum bagging technique. This technique is similar to the hand layup technique, except rather than consolidating the fibers by hand, a vacuum bag is applied over the laminate, and all of the air in the bag is removed to create a vacuum (shown in Figure 2). The result is a highly compressed laminate with a consistent resin content and reduced overall weight. The result of the curing process being completed under vacuum is that there is less exposure to toxic chemicals and gasses that are the by-product of the curing process.

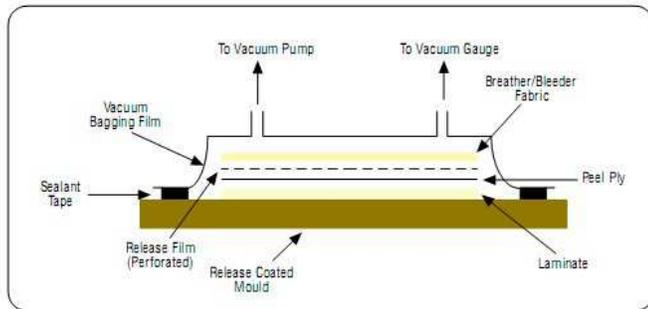


Figure 2 - Vacuum Bag Method

Construction Materials

Conventional lifeboat construction has used basic E-glass layup schedules in an effort to reduce material and labor costs. Additionally, because these conventional construction materials met all the strength requirements there was no need to explore modern, and typically more expensive, materials. Specifically, the materials and techniques traditionally used in the construction of lifeboats were such that the final lifeboat construction was able to pass the required Life Saving Appliance (LSA) tests. These tests simulated both an uncontrolled lifeboat drop from 3.5m and an impact with the side of a ship at ** m/s. Lifeboats operating in ice experience higher loads than those operating in open water. The experiment considers if the inclusion of Aramid (more commonly known as Kevlar™) on the outside skin of the panel improves the panel's ability to resist failure from impact.

E-glass has a number of properties that make it attractive for marine vessel construction. The material has good tensile and compressive strength, and is relatively inexpensive to produce and acquire. These attributes have led to E-Glass being the most common form of reinforcement fiber used in composites.

Aramid is a more modern material that is becoming increasingly common in the marine industry. It is a synthetic fiber that has both high strength and low density. Aramid has an excellent ability to resist

puncture. One of the drawbacks of this material however is that it has low compressive strength, and degrades slowly if exposed to ultraviolet light.

The construction material factor has two different categorical levels that include panels built solely from E-glass and panels built with E-glass plus a 7 oz Aramid layer near the outer skins of both sides of the laminate.

Test Response

There were three responses considered in the impact experiments. The acquisition of each response is described below.

Maximum Applied Load

To measure the applied load, a load cell was placed in line with the hydraulic ram. The load cell captured the applied load, measured in kilopond's (kips), at a rate of 20 Hz. The load cell had a capacity of 650 kN (146 kips).

Deflection at Maximum Applied Load

A Linear Variable Differential Transducer (LVDT) was used to measure the deflection of the panel. This device captured the movement of the hydraulic ram in millimeters at a rate of 20 Hz. The LVDT was capable of measuring up to 254 mm (10 inch) of travel.

Impact Energy

The impact energy between the hydraulic ram and the FRP panel was calculated by integrating the area under the applied load versus deflection plot. It should be noted that the impact energy was calculated from the moment the ram began to apply load to the panel to the moment the maximum applied load was achieved.

Impact energy is an important response as it can easily be used to correlate the test data from this experiment to full-scale trials that have been completed.

Test Results

There were a total of 16 tests conducted to assess the impact strength of lifeboat laminate. There were no repeats conducted. The run description of the impact tests is presented below, Table 2.

Table 2 - Destructive Impact Testing Run Description

Run Number	Thickness mm	Temperature °C	Material	Construction
1	10	6	E-Glass	Hand Layup
2	16	6	E-Glass	Hand Layup
3	10	16	E-Glass	Hand Layup
4	16	16	E-Glass	Hand Layup
5	10	6	E-Glass with Kevlar	Hand Layup
6	16	6	E-Glass with Kevlar	Hand Layup
7	10	16	E-Glass with Kevlar	Hand Layup
8	16	16	E-Glass with Kevlar	Hand Layup
9	10	6	E-Glass	Vacuum Bag
10	16	6	E-Glass	Vacuum Bag
11	10	16	E-Glass	Vacuum Bag
12	16	16	E-Glass	Vacuum Bag
13	10	6	E-Glass with Kevlar	Vacuum Bag
14	16	6	E-Glass with Kevlar	Vacuum Bag
15	10	16	E-Glass with Kevlar	Vacuum Bag
16	16	16	E-Glass with Kevlar	Vacuum Bag

OBSERVATIONS

Tensile Testing

All experimental results were entered into the statistical software Design Expert (DE) for analysis. This program uses the ANOVA test to study the results and formulate conclusions. To complete the analysis the first consideration was what effects should be included in the model. To determine this one must observe the effects list provided by DE and see which effects have large percent contributions. The effects list indicated that heat treatment (C), pre-stress (E), the interaction between material type and temperature (AB) and the interaction between temperature and pre-stress (BE) had the highest percent contributions and thus should be included in the model. Because AB and BE are combined effects Design Expert automatically selected A and B to also be included in the model in order to have hierarchy.

There are three main assumptions of the ANOVA test. The assumptions were assessed prior to data analysis. The assumption of normality was satisfied by viewing the normal plot of residuals and confirming that all data points aligned well with the normal line. Next it was ensured that the variance of the data set was equally distributed around the mean. This was ensured by analyzing the residuals versus predicted plot which proved that all data points had roughly equal variance. The third main assumption of the ANOVA is that the data is random. This was verified by viewing the residuals versus run plot. It should also be noted that the box-cox plot was reviewed to determine if DE suggested a data transformation. There was no data transformation suggested.

When all assumptions were satisfied, the ANOVA results were studied. A confidence interval of 0.05 was used in this analysis and therefore any effect that had a p-value below 0.05 was significant. The ANOVA results are shown in Table 3, presented below.

Table 3 - Tensile Strength ANOVA Table

ANOVA for selected factorial model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value	Prob > F
Model	13656	6	2276	3.49	0.012	significant
A-Material Type	15.94	1	15.93	0.024	0.877	
B-Temperature	17.65	1	17.64	0.027	0.871	
C-Heat Treatment	2816	1	2816	4.321	0.048	
E- Pre Stress	8233	1	8233	12.63	0.0015	
AB	1321	1	1321	2.03	0.167	
BE	1250	1	1250	1.92	0.178	
Residual	16295	25	651			
Lack of Fit	2001	9	222	0.248	0.98	not significant
Pure Error	14293	16	893			
Cor Total	29951	31				

The results indicate that the model itself was significant with a p-value of 0.012 and the lack of fit was not significant with a p-value of 0.980, this is indicative of a good model. There were only two effects that proved to be significant with a confidence interval of 0.05: heat treatment and pre-stress. Not shown in the table is the R² and adjusted R² values that were calculated for the model. These values are 0.456 and 0.325 respectively. This indicates that the model is statistically significant, however highlights the fact that further work must be done to develop a more accurate model.

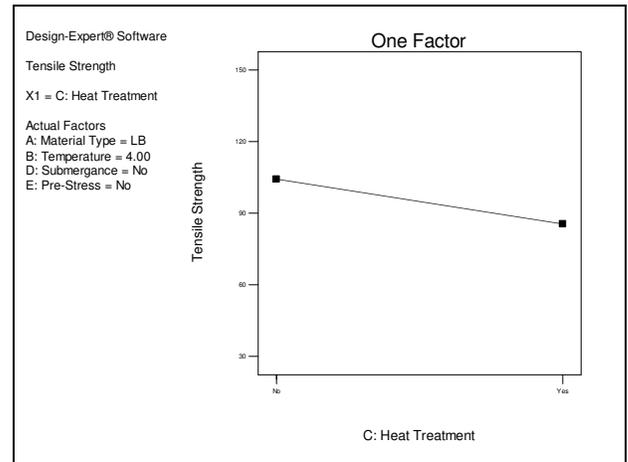


Figure 3 - Effect of Heat Treatment on Tensile Strength

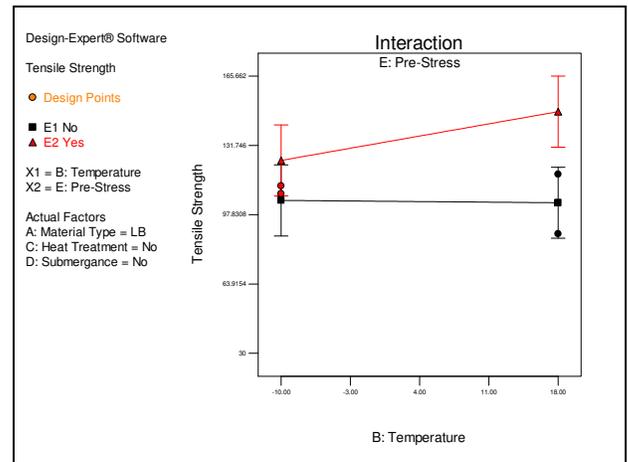


Figure 4: Interaction effect of Pre-Stress and Temperature on Tensile Strength

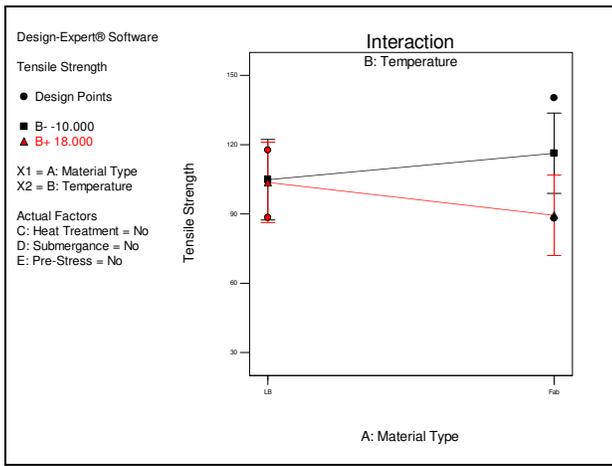


Figure 5: Interaction Effect of Temperature and Materials Type on Tensile Strength

Results collected through the used of Design Expert show that tensile strength was decreased when a specimen was exposed to the heat treatment (C). This is displayed in Figure 3, shown above. The interaction plots presented above, Figure 4 and Figure 5, show the interaction between pre-stress and temperature (BE) and temperature and material type (AB), respectively. Figure 4 shows that tensile strength is consistent across the temperature range if the specimen has not been exposed to pre-stress. However, it shows an increase in tensile strength as the temperature increases, if the specimen has been exposed to pre-stress. Figure 5 shows that temperature has little effect on the standard lifeboat panel's tensile strength. The same figure indicates an increase in tensile strength with a decrease in temperature if the panel is made to replicate the original lifeboat laminate.

Destructive Impact Panel Testing

The impact panel test results were also analyzed using the software package Design Expert. The results of both the impact energy and maximum applied load are presented below. The analysis of both responses followed the same procedure as the tensile test approach.

Impact Energy

The key factors affecting the impact energy were thickness (A), materials (C) and construction technique (D) as well as the interaction between thickness and materials (AC). This result is presented in the form of an ANOVA table, shown below in Table 4.

Table 4 - Impact Energy ANOVA Table

ANOVA for selected factorial model					
Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	df	Mean Square	F Value	p-value
Model	1089351	4	272337.7	13	0.0004 significant
A-Thickness	713141	1	713141.08	34.05	0.0001
C-Materials	83062	1	83062.98	3.97	0.0718
D-Construct	96328	1	96328.84	4.6	0.0552
AC	196817	1	196817.3	9.4	0.0107
Residual	230389	11	20944.51		
Cor Total	1319741	15			

The table shows that the model is significant and that the factors identified are significant with a confidence interval of 5%. Not shown

in the table is the R^2 and adjusted R^2 values that were calculated for the model. These values are 0.82 and 0.76 respectively. This indicates that the model is statistically significant.

The results of the impact energy analysis, shown in Figure 6 and Figure 7 indicate that the significant factors are laminate thickness, material type and construction technique. Additionally, the analysis showed that there was a strong interaction between thickness and material type.

In general it was found that the impact energy was highest for thicker panels for both E-Glass panels and E-Glass & Aramid Panels. It should be noted however, that thicker panels that contain Aramid have lower impact energy than those that are E-Glass only. Finally, it must be mentioned that panels constructed using the hand layup method had slightly higher impact energy than those that were vacuum bagged.

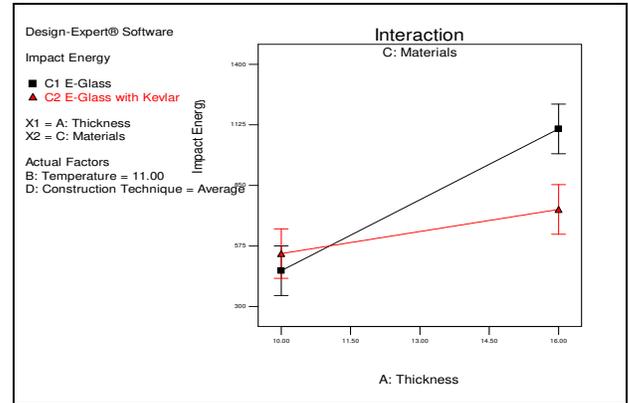


Figure 6 - Impact Energy Model - Thickness and Material Effects

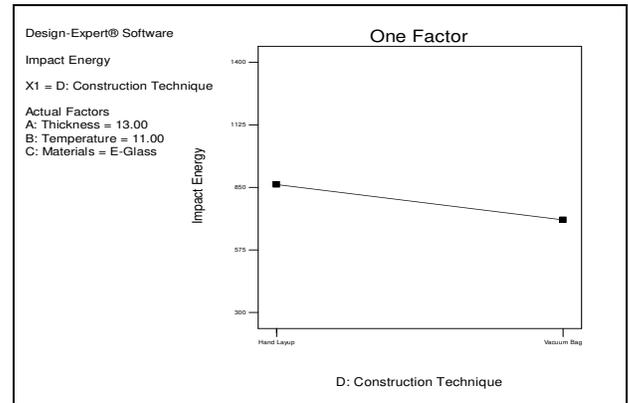


Figure 7 - Impact Energy Model - Construction Technique Effect

Applied Load

The key factors that were identified as affecting the maximum applied load through the experimental analysis were panel thickness, factor A, temperature, factor B, and materials, factor C. Additionally, the plot shows that there is an interaction between B and C and A and C. This result is presented in the form of an ANOVA table, shown below in Table 5. This table shows that the model developed is significant, based on a 5% confidence interval. Additionally, it shows that the identified factors are all significant based on the same confidence interval. The R^2

and Adjusted R^2 values for the model are 0.93 and 0.90 respectively. This is indicative of a statistically significant model.

Table 5 - Maximum Applied Energy ANOVA Table

ANOVA for selected factorial model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	2115	5	422.97	27.86	< 0.0001	significant
A-Thickness	1670	1	1670.40	110.04	< 0.0001	
B-Temperature	83	1	83.21	5.48	0.0413	
C-Materials	38	1	38.37	2.53	0.1429	
AC	240	1	240.08	15.82	0.0026	
BC	83	1	82.79	5.45	0.0417	
Residual	152	10	15.18			
Cor Total	2267	15				

The plots developed in the analysis are presented in Figure 8 and Figure 9. In general, as thickness is increased so is the maximum applied load. However, an interesting note is that for panels that are 10mm thick, if Aramid is in the panel the panel has a higher maximum applied load.

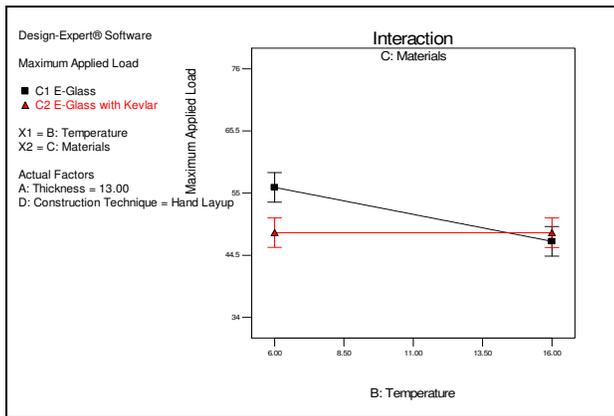


Figure 8- Applied Energy - Temperature and Material Effects

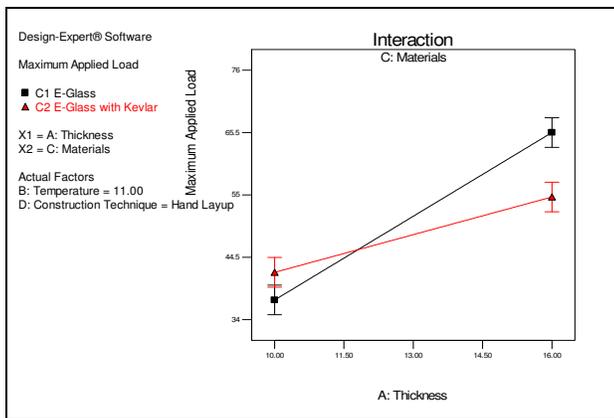


Figure 9 - Applied Load - Thickness and Material Effects

If the panel is 16mm thick and there is Aramid in the laminate, the maximum applied load is significantly reduced. Also noteworthy is the fact that in general, the maximum applied load is highest for low temperature conditions. Furthermore, if the laminate contains Aramid and is at a low temperature the maximum applied load is higher than if the laminate is only E-glass. At the higher temperature this effect is significantly less obvious.

RECOMMENDATIONS

Recommendations have been made based on the analysis of tensile and impact experiments. The recommendations are reviewed below.

Tensile Testing

Tensile test analyses lead to a number of findings that could improve the outcome of future laminate tensile testing. To begin, the submergence time was short (7 hours). The time should be lengthened in future tests to determine if a longer submergence would significantly affect laminate tensile strength.

Another recommendation relates to the clamping of specimens during testing. Some specimens tested encountered slip between the tensile machine clamps. As the force was applied some specimens gradually slipped out of the clamps. This could be seen as the test was occurring since the force displacement graph would cut off. When this occurred the specimen had to be re-clamped and retested. The initial force could have affected the maximum stress it could withstand upon retesting. Future tests could prevent this issue by sanding specimen edges, making them rougher and less susceptible to slip.

Destructive Impact Panel Testing

Panel testing involving chilled specimens should be conducted in a cold room. This will ensure a constant and consistent cold temperature for all specimens as well as ensuring that there is only a limited temperature gradient within the specimen. This should lead to less error in the results.

It would have been desirable to be able to complete a set of replicate runs for the experiment. These would have allowed for an error analysis to be completed as well as giving the data more certainty.

It should be noted that because this was a preliminary study of the impact resistance of a fiberglass plate, care must be taken in extending the results acquired and presented in this paper to true design problems. The testing focused on four panel constructions primarily constructed with E-Glass, and some reinforced with Aramid. Testing presented in this paper represents the testing that was completed. With that said, it is recommended that future work be completed to determine the effect of Aramid when located at both the extreme fibers, as was tested in this program, and at the neutral axis, proposed for future testing.

Future tests

Future tests conducted on replicated laminate should allow for adequate cure time as recommended in Gurit (2007). This will ensure that the specimens are fully cured and at optimal strength prior to testing.

Additionally, future testing should examine a larger temperature range. If lifeboats are to operate in both a temperate and arctic environment, testing will need to consider a minimum range of 30°C to -40°C.

Testing conducted to date has focused primarily on establishing the primary factors that affect the responses that have been measured. Future testing may wish to focus more directly on developing a detailed analysis of the responses that are significant. This would require the addition of center points and axial points in the experimental design. Doing this would result in the ability to extend the developed model beyond the current linear model that is presented within the paper.

In addition to this, there are still a number of variables that could be tested. These factors could include exploring cored panels, post curing panels, and using different types of resin. Furthermore, as fiberglass laminates are a highly customizable in their design it would be advantageous to determine whether different fiber types, and fiber orientations would have a significant effect on the panels impact resistance.

It is clear that lifeboats will need to be built with increased strength properties, but it is also clear that an effort will need to be made to maintain a light structure. Weight is a sensitive issue because these small craft spend most of their lives being carried by larger vessels, and

minimizing the overall weight improves the efficiency of the whole system.

CONCLUSIONS

The tensile tests concluded that pre-stress & temperature, material type & temperature and heat treatment significantly affect the strength of laminate material. The tensile tests were successful in determining the tensile strength of lifeboat laminate and assessing significant factors. A positive finding was that replicated laminate behaved similar to lifeboat laminate in terms of tensile strength. This allows for future testing to be performed on replicated material that is cheaper and more accessible than actual lifeboat laminate.

The destructive impact testing concluded that laminate thickness, material and construction technique had a significant effect on the impact energy of the test samples. Additionally, the experiment showed that temperature, material type and laminate thickness had a significant effect on the applied load. Two important findings indicated that there was not an appreciable increase in strength when a panel is cured under vacuum and that panel strength increased as the panel temperature decreased.

The results of this analysis could be applied to the structural design of any small laminate craft operating in harsh conditions. A relevant application is the design of a structurally enhanced lifeboat capable of operation in ice. With that said, it should be noted that the results presented in this paper are applicable only to the laminates that were

tested. This is primarily due to the highly variable strength of composites, as they depend highly on the composite's design, and the preliminary nature of the study itself. Further research, as discussed above, will help to develop a knowledge base that can be broadly applied to specific design problems.

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