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Mechanical Properties and Homogenous Analysis of Semirigid Polyurethane Foam used in Headliner Roof Top Manufacturing Process

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Abstract

In the automotive industry with four wheels or more, polyurethane is used as the main material in making roof top headliners. The process of making roof top headliners often experiences product defects, namely breaks (cracks or fractures). The study was conducted to analyze the homogeneity of mechanical characteristics at various positions in one block of polyurethane foam that had been cut into sheets with a thickness of 8 mm. Samples were taken representing vertical and horizontal positions and tested using the true experiment spatial sampling method. From this study, it was found that the density in one block of semi-rigid polyurethane foam was not homogeneous. There were differences in density in the upper, middle and lower materials in zones 1 to 9. The density value is directly proportional to the bending strength value and inversely proportional to the elongation value. In the zone where the elongation value is low, there is a risk of product defects in the form of fractures if the product's formability strength simulated using NX software is higher than 18%.

Keywords: *formability; simulation; semirigid polyurethane foam; true experiment*

Abstrak

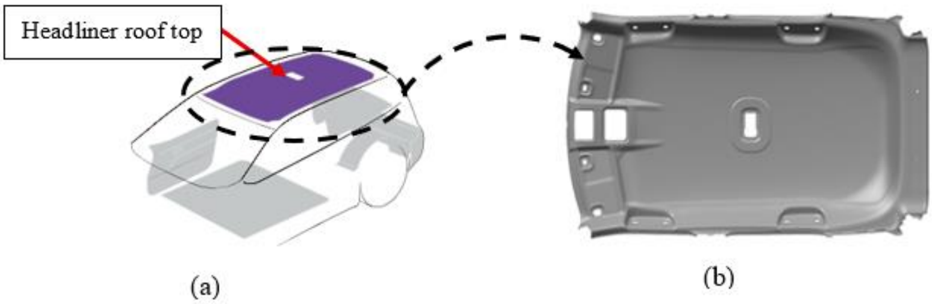
Di industri otomotif roda empat atau lebih polyurethane ini digunakan sebagai bahan utama dalam pembuatan headliner roof top. Proses pembuatan headliner roof top ini kerap kali mengalami cacat produk yaitu break (retak, pecah, patah). Penelitian dilakukan untuk menganalisa homogenitas karakter mekanis pada posisi yang beragam dalam satu blok polyurethane foam yang telah dipotong dalam bentuk lembaran dengan tebal 8mm. Sampel-sampel diambil mewakili posisi secara vertikal dan horizontal dan dilakukan pengujian menggunakan metode true experiment spatial sampling. Dari penelitian ini didapatkan hasil bahwa densitas dalam satu blok semi rigid polyurethane foam tidak homogen. Terdapat perbedaan densitas pada material bagian atas, tengah dan bawah pada zona 1 hingga zona 9. Nilai densitas berbanding lurus dengan nilai bending strength dan berbanding terbalik dengan nilai elongation. Pada zona dimana nilai elongation rendah timbul resiko munculnya cacat produk berupa fraktur jika kekuatan mampu bentuk produk yang disimulasikan menggunakan software NX lebih dari 18%.

Kata Kunci: *formability;* simulasi; *semirigid polyurethane foam; true experiment*

1. Introduction

Semirigid Polyurethane Foam (SR-PUF) is chosen as one of the core materials that are suitable in four-wheels automotive industry because of its material character that can be adjusted for stiffness, good acoustic ability, dimensional stability in high temperatures and good thermoformability [1] [2] [3]. Semi-rigid polyurethane foam is one type of foam made from polyurethane and can be used as headliner roof top in car manufacturing industries. The hard segment has a dominant influence that affects the overall characteristics of the material such as strength, hardness, and stiffness [4].

In the production process of the headliner roof top, it is often found product defect in the form of cracked, broken, fractured in *the* front pillar RH-LH area. Figure 1(a) illustrates a fully assembled headliner roof top installed inside a vehicle, showing its final application in the automotive interior. This provides a real-world context for the component under study. Figure 1.(b) presents position and a standalone view of the headliner product before installation, highlighting its structural form and surface characteristics. Figure 2.(a) shows a close-up view of a fracture or crack defect on the headliner surface, demonstrating the type of failure observed during production. Figure 2.(b) identifies the specific location where such defects commonly occur—typically in the front pillar areas (RH-LH sides) of the headliner. These zones experience high strain during thermoforming, and this figure emphasizes the practical motivation for the study: to investigate the root cause of these localized failures linked to material inhomogeneity.



.**Figure 1**. Headliner Roof Top, (a) after installed on the car's roof and (b) product.

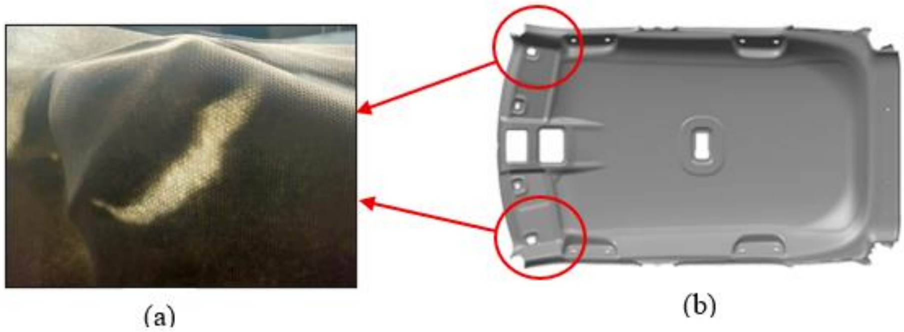


Figure 2. Product defect on headliner, (a) break, (b) point of occurrence of breaks

In previous research, Wegryzk et al. (2023) searched connection causality between variable *mixing pressure* on the *pouring* machine under high pressure to characteristic physical properties of polyurethane foam produced [5]. In his observations, the higher use of mixing pressure will cause pores tend to be larger with a wide range of size variations. The increase in the average pore diameter occurs because the higher the pressure used, the more turbulent the fluid coming out from the mixing head nozzle. This turbulence will affect the rate of chemical reaction of the two materials being mixed. While the varying size range occurs because some of the bubbles burst, causing a larger air space. The pores formed will affect the physical properties of semi-rigid polyurethane foam. Pores formed with a small average size will provide stiffer properties compared to materials with larger pores. This means that materials with smaller pore sizes have denser densities, higher tensile strengths but has greater tensile strength low.

K. Choupani et al. (2017) also concluded that foam with a higher isocyanate content has a higher density so that the compressive strength is better than foam with a low isocyanate content [6]. However, this increase in compressive strength will also affect the foam's flexibility, where the higher the density gives more risk for foam to be broken.

The present study represents a focused investigation and analysis to prove the homogeneity of physical characteristics within a block and seek causal relationships to product defects that occur during the roof top headliner manufacturing process. This study addressing a significant gap in current scientific knowledge about semirigid polyurethane foam that used in manufacturing process. This sutdy is also expected to give significant contribution and insights to the field of material engineering and composite material for headliner roof top manufacturing process.

2. Material and Method

2.1. Material and Foam Production Process

This study uses a true experimental spatial sampling method to determine the homogeneity of semi-rigid polyurethane foam (SR-PUF) characteristics. The term "fixed variables" in this research refers to the specific materials and formulation ratios that remain constant during the entire experiment. The materials used are isocyanate Elastoflex KE3980 CB, polyol Elastoflex PE3953/101, and a blowing agent in the form of air (H_2O). The ratio between isocyanate, polyol, and blowing agent was kept constant throughout production to ensure that any differences in results were due to positional variations within the foam block, not formulation changes [7]. The studied variables in this research are the mechanical properties—tensile strength, elongation, bending strength, and density—measured at different vertical and horizontal positions in the SR-PUF block [8].

The SR-PUF production process began by pre-mixing process. Each material was pre-mixed separately to homogenize additives and temperature after stored for several weeks. Pre mixing process takes time about 3-5 minutes. Then, the material will transferred to a temperature conditioning tank so each material eligible to transferred to next process. When the required temperature is achieved then both of material mixed together in mixing head with certain parameter such as mixing pressure (bar), mixing air (l/min), and rpm. Using the one-shot mixing method on a Hennecke 5000 low-pressure foaming machine, the pre-mixed isocyanate and polyol were combined in the predetermined ratio along with the blowing agent. The mixture was blended for a short, controlled time to initiate the polyurethane foaming reaction, then poured into a mold of specified dimensions. The mold was kept at a controlled temperature to promote uniform cell formation during foam rise. After approximately 30 minutes—sufficient for the foam to rise and complete initial polymerization—the block was demolded and placed in a controlled environment for a 72-hour curing period to allow complete chemical crosslinking and stabilization of the foam's mechanical properties [9].

2.2. Sampling Method and Mechanical Procedure

After stored for approximately 72 hours to complete the curing process then the material cut into 80 sheet with thickness of 8mm each. It is important to note that the material at the bottom of the mold before cutting becomes the top layer of the block after cutting. For vertical sampling, sheet #2 (top), sheet #40 (middle), and sheet #79 (bottom) were selected. For horizontal sampling, each sheet was divided into 9 zones, identified with codes such as A1 (top sheet, zone 1) and T2 (middle sheet, zone 2), yielding a total of 81 test samples. Mechanical testing was performed to measure tensile strength, elongation, and bending strength using an ISO 1798:2008-compliant procedure for tensile and elongation, and a 3-point bending method with specimens sized 160 mm × 25 mm. Density measurements were performed using an analytical balance.

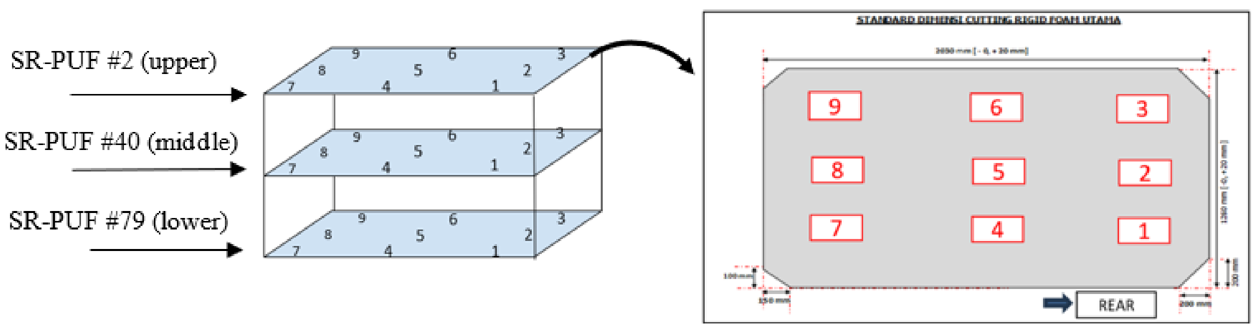


Figure 3. Zone 1 – zone 9 area on the upper, middle and lower layer of foam

Then each zones were sampled to determine the characteristics horizontally. Each zone on each sheet will be given a different identity such as A1 (upper sheet; zone 1), T2 (middle sheet; zone 2) and so on. Thus, a total of 81 test samples will be obtained. It should be noted that the majority of break product defects occured in zones 7 and 9. This schematic diagram illustrates in Figure 3, the division of each foam sheet into nine distinct horizontal zones (labeled 1 to 9), arranged in a 3×3 grid. The figure demonstrates the spatial sampling strategy used in the study to analyze mechanical property variations across the surface of the foam.

The variables to be tested includes tensile testing, elongation and bending strength. Tensile and elongation tests were carried out following the ISO 1798:2008 standard. While for bending testing, a specimen measuring 160 mm x 25 mm was used with the 3 method point bending test. Tensile, elongation and bending testing done use UTM machine with a capacity of 20 kN with speed of 10mm/min. While density test used Analytical Balance machine. Figure 4.(a) shows the Universal Testing Machine (UTM) used to perform tensile and bending strength tests at a constant crosshead speed of 10 mm/min. Figure 4.(b) depicts the analytical balance used for precise density measurements based on sample mass and volume. Figure 4.(c) displays the standardized specimen geometry used for mechanical testing, including tensile, elongation, and bending tests.

3. Result and Discussion

3.1. Experimental Results of Mechanical and Density Distribution

The results of the density test show a different distribution of density values between the upper, middle and lower zone materials. Likewise with the distribution of density values horizontally where the density values of zones 1 to 9 have differ as illustrated in Figure 5.

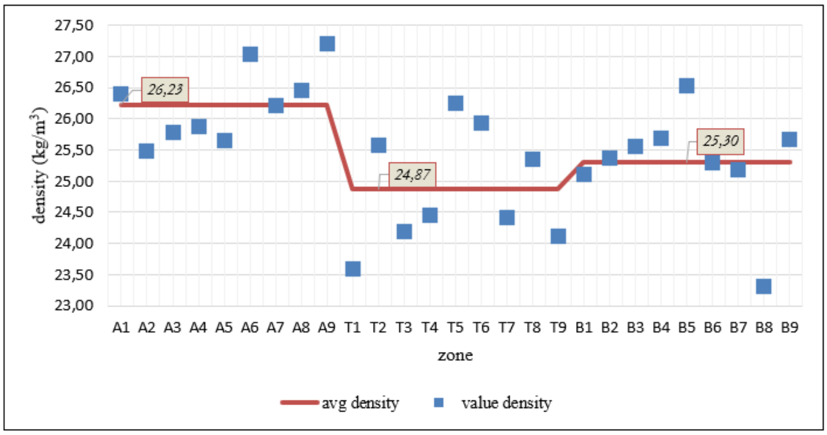


Figure 5. Density chart for all zones

Average density value for upper sheet is higher compared to the average density value of the middle and bottom materials. The average density value of the upper material is 26.23 kg/m^3 while the average density value of the middle material is only 24.87 kg/m^3 and the lower material is 25.30 kg/m^3. While the difference in horizontal position does not show a certain tendency or pattern on each of the top, middle and bottom sheets.

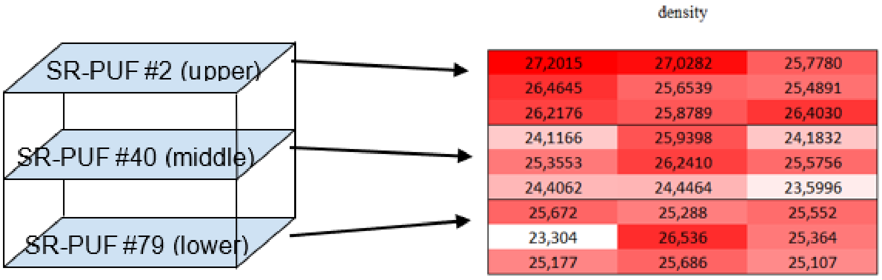


Figure 6. Distribution of density data for each layer

Based on data distribution that can be seen from Figure 6, the density of the upper material has a narrower variation range about 25.49 kg/ m^3 to 27.20 kg/m^3 or a difference in value of 1.71 kg/m^3. While in the middle material the variation range is 23.59 kg/m^3 to 26.24 kg/m^3 or a difference in value of 2.64 kg/m^3 and in the lower material the variation range is 23.30 kg/m^3 to 26.53 kg/m^3 or a difference in value of 3.23 kg/m^3. Thus it can be concluded that the upper material has better density homogeneity than the middle and lower materials.

The higher density distribution upwards can be understood because the material after the cutting process is placed in an inverted arrangement. Basically, the upper material after the cutting process is the lower material during pouring so the lower material gets greater pressure due to gravity and makes density becomes higher [10].

Density that is not homogeneous both vertically and horizontally will give potential different characteristic on the foam. Therefore, further testing was carried out to prove the relationship between the influence of density on tensile strength, elongation and bending strength in each zone. The results of the elongation test prove that the upper material has a lower average elongation value compared to the average elongation of the middle and lower materials. The average elongation value of the upper material is 10.23%, lower than the average value of the middle material which is 13.34% and the lower material which is 13.70%, as presented in Figure 7.

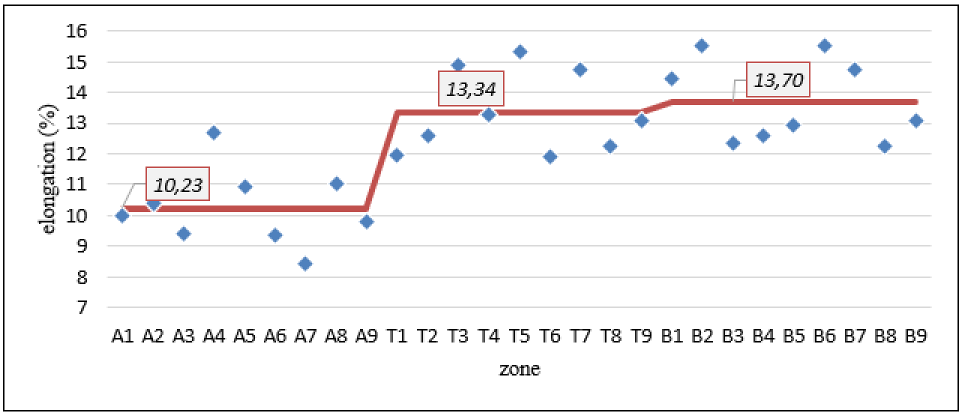


Figure 7. Chart of elongation for all zones

The average elongation value of the upper material is inversely proportional to its density. This can happen because the process of making semi-rigid polyurethane foam uses low pressure machine with a mixing pressure parameter of 10 bar. Wegrzyk. G (2023) also conducted research to look for connection between mixing pressure variable on a high pressure machine. In his observations , the higher mixing pressure will cause pores tend to vary greatly and the average pore diameter figures are tend more big compared to low pressure machine. This is seen clearly when compare the foam elongation made using mixing pressure 170 bar and mixing pressure 110 bar.

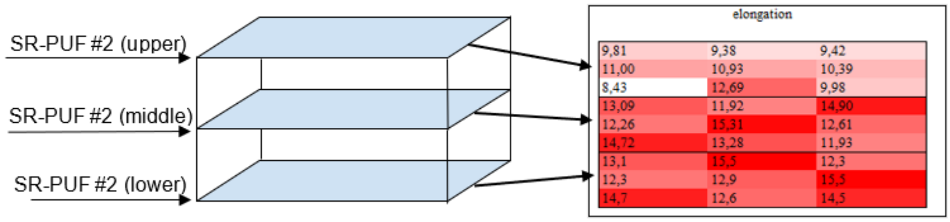
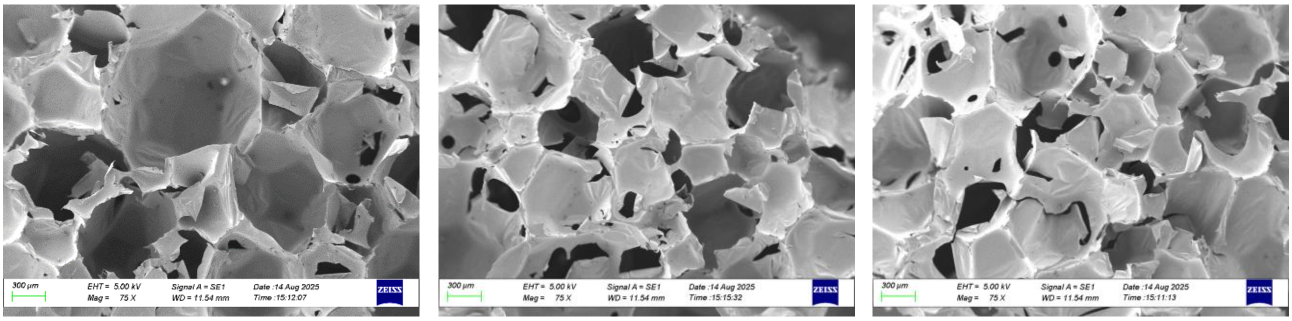


Figure 8. Distribution of elongation data for each layer

The semi-rigid polyurethane foam made with high pressure machine will cause turbulence when the fluid is shot into the mold. This turbulence will affect the rate of chemical reactions and cause the pores formed in the foam to tend to be larger [11]. In some cases, the pores in the foam break so that the broken pores join with other pores and leave a larger air space[12] [13]. This has an impact on materials with large pores which means they have longer soft segments than hard segments and tend to have higher elongation rather than small pores [14]. Figure 8 explain that upper material dominated by small pores (because it's origin before cutting process is in lower position and made by low pressure machine) so it has lower elongation value.

Scanning Electron Microscope (SEM) images showing the microstructure of the foam at different vertical positions. Figure 9. (a)–(c) reveal that the upper layer (c) has smaller, denser, and more uniform pores, while the lower (a) and middle (b) layers exhibit larger and more irregular pores. This microstructural evidence directly explains the observed mechanical differences: smaller pores correlate with higher density and stiffness but lower elongation.



(a) (b) (c)

Figure 9. Pore size viewed on SEM, (a) lower material, (b) middle material, (c) upper material

Meanwhile, for the bending strength test, the material in the upper part which have smaller pores tends to have a higher average bending strength value [15] compared to the material in the middle and lower parts. The average bending strength value of the upper material is 136.06 kPa, higher than the average value of the middle material which is only 98.92 kPa and the average value of the lower material is 107.68 kPa, as presented in Figure 10.

The bending strength tends to be higher in line with research that has been conducted by K. Choupani (2017). In his research, it was stated that density has a positive correlation with compressive strength, where the higher the density value, the higher the compressive value. As explained in the previous section, upper material have higher density and it can be concluded that upper material tend to have higher bending strength value compared to middle and lower material. Using a heatmap table as seen in figure 11, it's clear that upper material have higher bending stregth value than others.

Although pore density also can be influenced by the mixing pressure. In his research the higher the density used, more the pores tend to become denser, thus increasing compressive strength value [16].

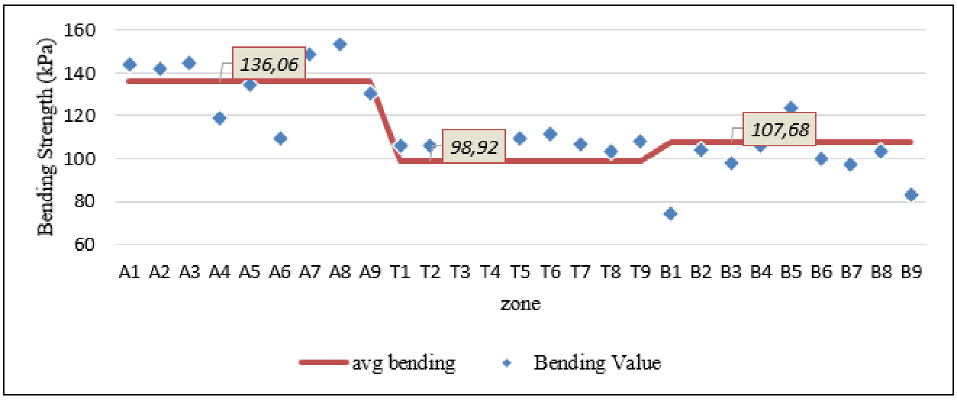


Figure 10. Chart of bending strength of all zones

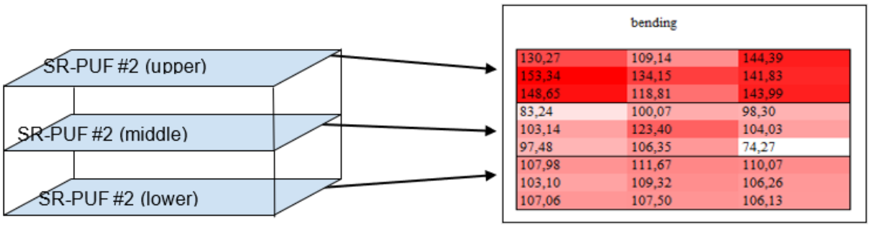


Figure 5. Distribution data of bending strength for each layer

Tensile test is carried out to see connection between density and tensile strength in each zone. The results of the test showed no particular pattern or tendency between density and tensile strength in each zone. C. Oppon. et al. (2015) in his research stated that tensile strength will increase if the ratio between isocyanate and polyol is increased. Increasing the ratio from 50:50 to 45:55 will increase the tensile strength from 430 kPa to 516 kPa or an increase of 20%. Tensile testing in this study was carried out on materials with the same isocyanate to polyol ratio and became a fixed variable and from this study it was concluded that tensile strength tends to be the same in the upper, middle and lower materials. Test result as seen in Figure 12 shows there is no significant difference between upper, middle and lower material.

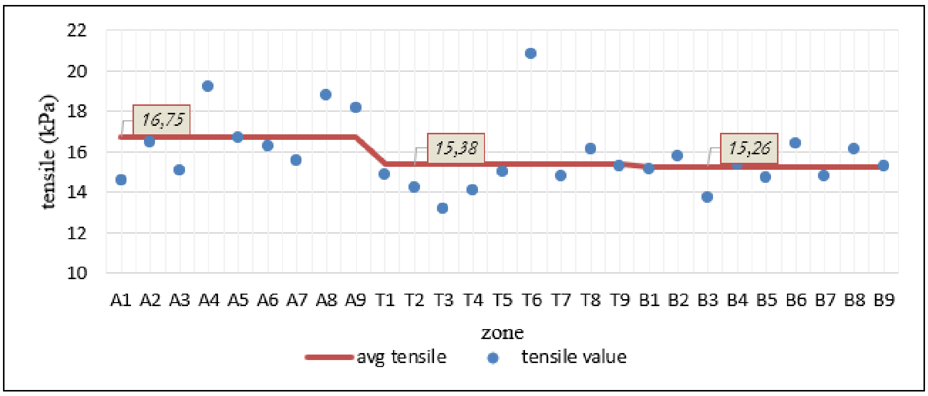


Figure 6. Chart of tensile strength

3.2. Correlation Analysis and Implication for Product Defects

To determine the correlation of the mechanical characteristics of semi-rigid polyurethane foam to product defects that appear on the headliner roof top front pillar area RH-LH, a simulation was carried out using NX software. This simulation aims to determine the formability of the semi-rigid polyurethane foam material. Given that the rooftop headliner is designed symmetrically on the right and left sides, the zone division illustrated in Figure 13.(a) presents a 3D isometric view of the entire headliner, highlighting its complex curvature and symmetry. Figure 13.(b) superimposes the simulation domain generated in NX software onto the corresponding physical sample zones, mapping zones 1–9 to the actual product geometry. This alignment enables a direct correlation between experimental results and simulation outputs, thereby validating the analysis of formability and identifying regions of stress concentration.

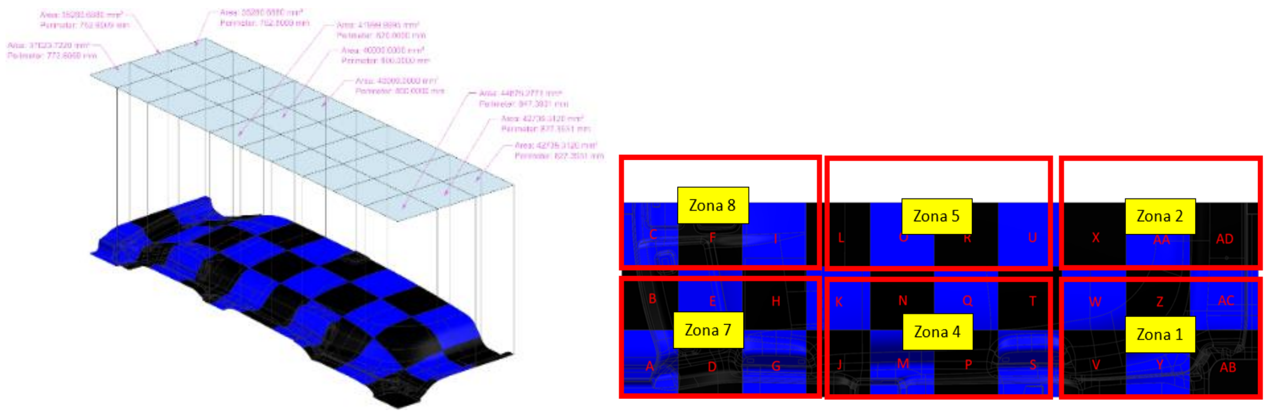


Figure 7. (a) Isometric view of headliner roof top; (b) NX Simulation compared to sample zone

	Luas Area Part	Luas Area Mat	Formability %	
A	49190,7	37023,7	33%	Zona 7
B	39750	35260,6	13%	
C	41086,4	35260,6	17%	
D	51917,5	41999,9	24%	Zona 7
E	42837,1	40000	7%	
F	43251,6	40000	8%	
G	51549,8	41999,9	23%	Zona 7
H	40669,1	40000	2%	
I	40656,1	40000	2%	
J	49674,1	41999,9	18%	Zona 4
K	40286,8	40000	1%	
L	40015,9	40000	0%	
M	48815,8	41999,9	16%	
N	40355,8	40000	1%	
O	40139,1	40000	0%	
P	49058	41999,9	17%	
Q	40409,6	40000	1%	
R	40304,3	40000	1%	
S	52099,9	41999,9	24%	Zona 4
T	40476,1	40000	1%	
U	40059,2	40000	0%	
V	49220,3	41999,9	17%	
W	40847,3	40000	2%	
X	40129,4	40000	0%	
Y	44341,5	41999,9	6%	
Z	45815,7	40000	15%	
AA	45290,5	40000	13%	
AB	51497,6	44876,2	15%	
AC	47262,4	42739,3	11%	
AD	48500,2	42739,3	13%	

Figure 8. Formability of semi rigid polyurethane foam

The simulation results using NX software are then summarized in a table stating the percentage of formability of each part of the semi-rigid polyurethane foam using the formula.

$$formability = \left(\frac{parts\ area}{materials\ areal}\right) - 1 \quad (1)$$

The greater the formability value, the greater the semi-rigid polyurethane foam material experiences bending loads, thus giving a high risk of fracture if its elongation capacity is low. This can be seen in Figure 14 where zone 7 has a higher formability value compared to other zones. As seen in figure 14, high formability value located in [A] 33%, [D] 24%, and [G] 23%. Zone 4 is also have a high value 18% and 24% but not the point of occurence of fracture as previously seen in figure 2. But, it also provide information that the area is prone and tend to fractures.

4. Conclusion

Based on the research data that has been conducted by the author above, it can be concluded that the mechanical characteristics of semi-rigid polyurethane foam are not homogeneous either vertically or horizontally. However, the difference in mechanical characteristics has a clear pattern when observed vertically. The density of the material at the top has a higher average value of 26.23 kg/ m^3 , while the average density of the middle material is only 24.87 kg/m^3 and the bottom material is 25.30 kg/m^3. The high density of the material at the top is inversely proportional to its elongation which has a low average value of 10.23%, lower than the average value of the middle material of 13.34% and the bottom material of 13.70%. In the bending test, the upper material had a higher average bending strength value compared to the materials in the middle and bottom, namely 136.06 kPa, higher than the average value of the middle material which was only 98.92 kPa and the average value of the lower material which was 107.68 kPa.

Low material elongation on the top material poses a risk of product defects during the manufacturing process of the headliner roof top even though the material on the top also has a high bending strength value. This can be explained because the manufacturing process of semi-rigid polyurethane foam is carried out use machine under pressure low with 10 bar mixing pressure. Low mixing pressure This will causing the pores that are formed to tend to have a larger diameter small compared to If made use mixing pressure high on the machine high pressure which will have an impact on the diameter of the pores produced to be larger. Smaller and denser pores mean that they will provide brittle or stiffer properties to the final result of semi-rigid polyurethane foam material. This is increasingly clear after the author conducted a simulation of *the formability* of semi-rigid polyurethane foam material using NX software where the results were that zone 7 and zone 9 experienced the highest buckling load compared to other zones, namely 33% [A], 24% [D], 23% [G].

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