Investigation of Mechanical Properties for Unsaturated Polyester-Based Fibre Glass Composites Filled by Recycled Milled Composites

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Abstract. The present study discusses the mechanical properties of a composite material consisting of polyester resin reinforced by random mat glass fiber and milled of (scraped material) waste of glass-reinforced pipe (GRP). The current work uses the finite element method based on ANSYS program as a tool for evaluating the performance of the design proposal for the car roof. The milled wasted glass fiber composite has showed a good and acceptable young modulus, maximum stress, and yield strength compared with the random mat composite. The agreement of the suggested material comes from the experimental and theoretical results for some of the laboratory tests. The divergence between results of random mat glass fiber and milled waste glass fiber do not exceed the percentages errors that are obtained during experimental work, which are 3.98% and 5.26% for tensile strength and strain until failure in the tensile test, 4.5% and 3.6% for flexural strength and strain in bending test and 12.32% and 1.27% for strain energy and deformation in the impact test, respectively. The result of the numerical solution was compatible with the experimental results. The result extracted from this study proved that the milled of waste of glass fiber composite is an acceptable reinforcement material with economic and environmental benefits.

Keywords. Car roof, Polyester resin, Milled glass fiber, Waste fiber, Glass reinforced pipe.

| Abbreviations and Symbols | Equation |
|---------------------------|----------|
| GRP                       | glass reinforced pipe |
| RMGF                      | random mat glass fiber |
| MGWF                      | milled of waste glass fiber |
| ASTM                      | American Society for Testing and Materials |
| $\sigma$                  | Stress |
| $C$                       | constitutive matrix |
| $\epsilon$                | Strain |
| $\tau$                    | Shear stress |
| $\gamma$                  | Shear strain |
| $Q$                       | Constant of the stress-strain relation |
| $E$                       | Modulus of elasticity |
| $p_m$                     | Matrix density |
| $\psi$                    | Constant function to poisons ratio |
| $\nu$                     | poisons ratio |
| $G$                       | Shear modulus |
| $T$                       | transformation matrix |

$c$ Cosine of fiber orientation
$s$ Sine of fiber orientation
$\theta$ Angle of fiber
$F$ Applied force
$L$ Length of specimen
$b$ Width of specimen
$d$ Thickness of specimen
$FVF$ Fiber volume fraction
$\rho_f$ Fiber density
$[K]^e$ Stiffness matrix of the element.
$[\epsilon]^e$ Displacement vector of the element.
$[F]^e$ Force vector of the element.

Abbreviations and Symbols: GRP - glass reinforced pipe, RMGF - random mat glass fiber, MWGF - milled of waste glass fiber, ASTM - American Society for Testing and Materials.
1. Introduction
Fiber-reinforced polymers play a significant and important role in modern engineering applications because of their rare specifications and features, which made them the most used in manufacturing many engineering parts. Among the most important of these characteristics or specifications are lightweight and a relatively low density compared to other materials, high resistance, corrosion resistance, and fatigue resistance [1,2]. The characteristics and techniques of manufacturing the fiber-reinforced composites that ideal for essential applications and specifications of their outstanding performance, making composite materials a promising alternative to metals or alloys [3]. Previous studies discussed in details the benefits of using the composite materials in each part of the car, such as bumper, hood or cap and lightweight roof structure and the applicability of advanced reinforced polymers to car components and the advantages and disadvantages of composite analysis simulations [4, 5]. The composite bonding patches were used for carbon/epoxy laminate composite structures repairing with different sequences of symmetric stacking using a 3D numerical method to determine the releasing of energy rate [6]. Also, an analytical approach was investigated for the stresses in RC beams supported by on the outside bonded GFRP laminate prestressed depended on the boundary conditions and equilibrium equations [7]. The evolution of engineering materials and methods selected based on the characteristics of these materials and their role in crashworthiness provided by the designers are excellent for the development of modern designs and offer distinct safety conditions, as well as the conditions presented to users through more significant safety components, are mostly made of plastic material, such as polycarbonates, thermoplastic olefins polyamides, polyurethanes, polypropylene, polyesters, glass fiber...etc [7]. The integration of design mainstay in terms of constituent materials, on the one hand, and in terms of structural design fitting, on the other hand, has showed better safety conditions for vehicle components and passengers [8]. With the development of computer hardware and the development of techniques of information processing orientation studies to use the finite element method (finite elements) to evaluate the performance of collision resistance of those components, such as roof, bumper and develop specifications [9]. Some of the previous studies dealt with alternative systems to absorb the energy of collision and design of the material, such as glass, plastic-coated thermally in order to absorb the shock and not passing it to the body of the car, in addition to the aerodynamic forces [10,11]. Also, the absorption energy of certain components has been discussed the changes in the geometry and properties of the material of car components [12]. Another study discussed the most important factors, which include material, thickness, shape, and conditions for the the design and analysis of car safety components of the vehicle to improve efficiency or resist the work at specific conditions [13]. Other safety elements in the car, such as the frontal and rear bumper, were discussed based on the simulations numerical design elements of the safety of the vehicles, either optimized by changing the composition, increase the thickness, improve its performance, and the basic concepts of improving the safety of the car by the work of analysis to investigate the mechanical properties and the mechanism of failure [14-16]. The present work deals with a composite car roof structure to study the mechanical behavior of this component under different loading conditions by using a composite material of resin matrix reinforced by random mat glass fiber and waste of glass-reinforced pipe as milled through some of the standard mechanical laboratory tests, such as tensile, bending and impact tests. Also, numerical simulation is conducted using the finite element method based on ANSYS program to evaluate the performance of the proposed design.

2. Materials and methods

2.1. Materials
The upper roof of vehicle composite consist of several materials such as:

2.1.1. Resins (matrix). It is composed of unsaturated polyester resin, a liquid substance sticky semi-transparent. Polyester resin is made in Saudi Arabia, Tapaz 1110TP (pale yellow insoluble in waster, 1.2 g/cm3, 100 °C flash point) [17].
2.1.2. **Solidification agent.** Catalyst a material prefix to interact a substance organic peroxide, ranging from (1% - 3%) and by the required properties and time as increasing the proportion of solidified material lead to a lack of time drought resin after mixing any chemical reaction. As Also, on the way or mechanism of action they are spraying method by pumps or the way the paintbrush (should not be less than 1%) gives a long time to dry and this gives the plant enough time to work a minimum period of drought (30) minutes, this period is suitable to add layers and according to the manufacturing mechanism.

2.1.3. **Accelerators agent.** Cobalt (Octoate) accelerates the chemical reaction between the resin and the solidified material and proportions used very few times, especially in the times of cold weather as it leads to increase the speed of interaction and speed sclerosis.

2.1.4. **Reinforcement agent.** Including standard random mat glass fiber (RMGF) and milled of wasted glass fiber (MWGF) with volume fraction (14%) for each sample.

2.2. **Preparation of composite materials**

In the present investigation, the random mat glass fiber (RMGF) and milled of waste glass fiber (MWGF) from the waste of glass-reinforced pipe (1.75 g/cm³, 12-24 mm length) are used. The wasted glass fiber that is made of glass fiber reinforcements embedded in a cured thermosetting resin. GRP pipes combine the benefits of durability, strength, and corrosion resistance; moreover, they offer excellent design flexibility with the possibility to customize the pipe design in a wide range of properties [17]. In the present work, milled glass fiber was obtained from the recycling and isolation mechanical process of GRP damaged section, where they were taking the suitable sample from it and broken down into small parts by a hammer and then material pass through one stage gears to separate the greatest amount of polymer. Then, the fibers are separated from the residual polymer by using Los Angeles abrasion machine made by (AZMOON TEST Co.) with drum stroke (30-33 rpm), noise reduction cabinet (1.5 mm) thickness, twelve abrasion charges with (46-47 mm) diameter and (5000 gr) weight, then cleaned fiber is resulting by multi-pass sieves to ensure removal of milled polymer and separate it from the fibers. The obtained fibers are well grinded, as shown in Figure 1 and Figure 2. The volume fraction of fiber is about 14.24%, and FWF is 0.195 for random and milled waste composite.

The resin is well mixed with the hardener and accelerated material (if necessary), then the solidification starts. The specified surface for this process is by insulation material and added a layer from this mixture. This process is repeated until getting the required thickness for this layer; after that fibers layer (or other reinforcement agents) well added on the first layer. Then, a new layer of the resin will be added to cover the fibers; it is then left until the solidification process completes. It can be seen many things during the process, such as mounting vapors as a result of the added hardener and accelerator, in addition, increasing temperatures for survival periods depends on the thickness of the material. The present study includes different mechanical tests, such as tensile, bending, and impact test. The influence of car roof materials under different loads was correlated to the properties of the material to understand the performance of this important part.

![Figure 1. Waste glass reinforced pipe](image1)

![Figure 2. Section of glass-reinforced pipe](image2)
2.3. Testing of the composite

2.3.1. Tensile test. This method is containing procedures that used to evaluate the tensile properties of specimens according to ASTM D 3039 [18], where five samples per test (at least) at same preparing and testing conditions (23±3 C and 50 ±10% relative humidity …etc.) and the average of these results was considered to study and understand the mechanical behavior of these materials.

2.3.2. Bending test. For experimental determination of the flexural modulus, a three-point bending test was chosen. The test is based on ASTM D790-07. The form of the test specimen was a bar that has approximately 12.7 cm long and a rectangular cross-section. Supports were placed at 10.2 cm apart. The default radii of the loading nose and supports are both 5.0 mm. Bending strength is referred to the flexural strength or fracture strength. It represents one of the mechanical properties of materials, and shows their ability to withstand the bending deformation. The transverse bending test is most often employed, for a rectangular cross-section of the test specimen is bent until failure occurs using a three-point bending test technique. The bending strength measured in terms of stress [19].

2.3.3. Impact Test. Charpy tester was used to measure the failure resistance at suddenly applied forces and according to ASTM D6110-04. The specimens must be standardized in dimension, where the stress concentration and minimize plastic deformation availed by the specimen notch [20].

3. Numerical analysis

ANSYS program is useful software for design analysis in mechanical engineering. Powered by fast solvers, ANSYS V. 11 makes it possible for designers to quickly check the integrity of their designs and search for the optimum solution. There are several models and systems for the car roof. Traditional models have corrugated open section areas for installing some car elements and increasing bending strength. Car roof must be aerodynamic suitable, lightweight and aesthetically pleasing to the consumer. Shells could be used for the layered applications of a structural shell model or modeling thick sandwich structures and nonlinear layered structural shell. Shell99 allows more layers, the element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The roof dimensions were (2000 mm length × 1040 mm width × 2 mm thickness). The real boundary conditions and loading on the car roof like fixing conditions and applying loads from the aerodynamic, dead weight from material property, such as density and according to real dimensions for HYUNDAI/ SENTAIF car model. It is important to think about whether a free mesh or a mapped mesh is appropriate for the analysis before meshing the model, and even before building the model. A free mesh has no restrictions in terms of element shapes, and has no specified pattern applied to it. A mapped mesh is restricted in terms of the element shape it contains and the pattern of the mesh[21]. In the present work free mesh was used in order to treat the roof of the car as a case study, as illustrates in Figure 3.

![Figure 3. Meshing of car roof.](image-url)
Consider a laminated composite thin structure made of very thin layers of lamina composite material to derive stress-strain relationships. Each lamina material consists of parallel, continuous fibers of one material (e.g., glass, boron, graphite) embedded in a material of the matrix (e.g., epoxy resin). The primary purpose of the matrix material is to transfer shear stress between the fibers. This section focuses on isotropic and orthotropic materials to describe the constitutive relations. The Poisson's ratio ($\nu$) of the composite was used from the literature and it is 0.3. A composite structure, in this case, a laminate, is composed of stacking sequence orthotropic layers. For an orthotropic ply, the fibers are assumed to be distributed uniformly, thereby simplifying the constitutive relations. By applying the principle of linear elastic material behavior, the constitutive law, known as the generalized law of Hooke, provides the sought-after relationship [22].

$$\sigma = C \varepsilon \quad (1)$$

Here, through the constitutive matrix $C$, the stresses $\sigma$ are linearly related to the strains $\varepsilon$. Taking advantage of symmetry conditions and considering strain energy. It can be shown in Equation (2); the description of the anisotropic materials requires only 21 constants [23].

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{bmatrix} \quad (2)$$

The constitutive relationship of orthotropic materials is simplified, as described in the main material coordination system.

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{13} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0_{13} & 0_{14} & 0_{15} & 0_{16} \\ Q_{21} & Q_{22} & 0_{23} & 0_{24} & 0_{25} & 0_{26} \\ 0_{31} & 0_{32} & Q_{33} & 0_{34} & 0_{35} & 0_{36} \\ 0_{41} & 0_{42} & 0_{43} & Q_{44} & 0_{45} & 0_{46} \\ 0_{51} & 0_{52} & 0_{53} & 0_{54} & Q_{55} & 0_{56} \\ 0_{61} & 0_{62} & 0_{63} & 0_{64} & 0_{65} & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{13} \end{bmatrix} \quad (3)$$

In terms of engineering constants, the constants $Q$ can be described by [24]:

$$\begin{bmatrix} Q_{11} = \frac{E_1}{\psi}, Q_{12} = \frac{E_1 v_{12}}{\psi}, Q_{21} = \frac{E_2 v_{12}}{\psi}, Q_{22} = \frac{E_2}{\psi}, Q_{33} = E_3, Q_{44} = G_{12}, Q_{55} = \frac{G_{23} \psi}{\nu}, Q_{66} = \frac{G_{13} \psi}{\nu} \end{bmatrix} \quad (4)$$

Where; $\psi = 1 - \nu_{12} v_{21}$

In Equation (4) for multi- and single-layered structures, the factor $\alpha$ is the shear correction factor taken to be $5/6$. Here, nine independent constants, which were detailed by Hansen and Hvejsel [25], can describe the constitutive relationship between the stresses applied and the resulting strains. The $[T_\theta]$ transformation matrix for plane coordinate angle rotation $\theta$ is denoted by:

$$T_\theta = \begin{bmatrix} c^2 & s^2 & 0 & cs & 0 & 0 \\ s^2 & c^2 & 0 & -cs & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -2cs & 2cs & 0 & c^2 - s^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -s \\ 0 & 0 & 0 & 0 & s & c \end{bmatrix} \quad (6)$$

Where; $c = \cos(\theta)$ and $s = \sin(\theta)$.

The elements of $[Q_{ij}]$ matrix are defined as:

$$Q_{ij} = c^2 F_{ij} + s^2 F_{2j} - 2sc F_{4j} \quad (j = 1,2,4)$$
Where,
\[ Q_{2j} = c^2 F_{2j} + s^2 F_{1j} + 2sc F_{4j} \] (j = 1, 2, 4)
\[ Q_{33} = F_{33} \]
\[ Q_{4j} = sc F_{1j} - sc F_{2j} + (c^2 - s^2) F_{4j} \] (j = 1, 2, 4)
\[ Q_{5j} = c F_{5j} + s F_{6j} \] (j = 5, 6)
\[ Q_{6j} = -s F_{5j} + c F_{6j} \] (j = 2, 6)

Also, the flexural strength of the composites was calculated by [26]:
\[ \sigma_m = \frac{3FL}{2bdl^2} \] (7)

The volume fraction of fiber is about 14.24% and FWF is 0.195 for the random and milled waste composite that where calculated from the following Equation [27]:
\[ FVF = \frac{1}{1 + \frac{\rho_F}{\rho_m} \left( \frac{1}{FWF} - 1 \right)} \] (8)

The displacement approach from the solution of finite element problem is calculated from the following Equation [28]:
\[ [K]^e \cdot [\delta]^e = [F]^e \] (9)

4. Results and discussions

4.1. Tensile test results

Figure 4 shows that the breakdown of the tensile test occurs in the effective length. Also, the experimental force-extension curve illustrates the behavior of composite by computerized BESMAK machine.

![Figure 4. Tensile test specimen.](image-url)
results of milled waste glass fiber have high extension results to failure. In contrast, the random mat glass fiber has the highest extension value to failure, and this is related to the ability of these materials to carry most of the applied loads on the composite material while the matrix transferred these loads. Also, the result of milled glass fiber refers to the ability of this material to work as a reinforcement agent as it can correlate with the other components of composite material, and this attributed to the properties of the origin of these particles (glass fiber). The small size of these particles gives it a higher structure and large surface area where this leads to hinder the polymer upon straining and give relatively isotropic behavior in the composite. The behavior of these materials gives the same indication through theoretical results. These results are compatible with some researches that dealt with the effect of the surface quality on the mechanical properties of fiber-reinforced plastics such as (Ashok Rai et al., 2013)[29].

**Figure 5.** Theoretical and experimental force-extension curve.

Figure 5 also shows the experimental and theoretical force-extension results together; the deviation between the experimental and theoretical results is due to the initial defects of composites like blow holes, porosity, dust etc. , but the analysis part of the ideal part condition, such as isotropic behaviour, was considered, where that is not possible to achieve that practically, also these results consentient with (Satnam et al., 2013)[30]. The experimental results have a lower value for extension compared with the theoretical result except for the theoretical results of (MWGF), where it has lowest value for extension compared with the experimental result of (RMGF). Some of the mechanical properties can be calculated from the above results, as shown in Table 1. Finite Element Analysis (FEA) was used to simulate the tensile test outputs using ANSYS V.11 and showed acceptable results with 6.6% and 6.57% as the error percentages from the comparison between MWGF and RMGF in the theoretical and experimental tests for tensile strength, and 11.1% and 15.7% as the error percentages for strain until failure, respectively.

**Table 1.** Mechanical properties (tensile test result).

| Properties          | Experimental | Theoretical | Perc. | Error % |
|---------------------|--------------|-------------|-------|---------|
| RMGF                | MWGF         | RMGF        | MWGF  | RMGF    | MWGF    |
| Tensile modulus, GPa| 4.11         | 3.948       | 4.34  | 4.1     | 5.59     | 5.1     |
| Tensile strength (MPa)| 95.5        | 91.716      | 105   | 93.4    | 9.9      | 1.83    |
| Stress at fracture (MPa)| 59.3       | 56.952      | 63.2  | 60.7    | 6.57     | 6.6     |
| Strain till failure (%)| 3.8         | 3.6         | 4.4   | 4.01    | 15.78    | 11.1    |

4.2. **Bending test results**

The experimental and theoretical bending test results were shown in Figure 6. The experimental results of the milled waste glass fiber have high deflection results to failure, while the random mat glass fibers have the highest deflection value to failure. The mechanical behavior for these materials gives the same indication through theoretical results. The small size of milled particles gives it a higher structure and
surface area where this leads to hinder the polymer upon straining, and this is referred to as the ability of these particles to work as a reinforcement agent with the resin matrix. The stiffness of composites is increased because of the nature of fiber material, where fibers are lighter in weight but harder, which makes them stand high bending loads and capable of absorbing more resin that was affected in the maximum stresses, yield strength, and young modulus. Figure 6 also shows that the experimental results have a lower value for deflection compared with the theoretical result for all types of composite material specimens. The diverging between the experimental and theoretical results is related to the same reason that is previously discussed during the tensile test. It seems clear that the maximum fracture forces are the same for all composites. However, their deflections are different, and this reflects the response of these composites under the applied loads as mentioned previously.

![Figure 6. Theoretical and experimental force-deflection curve.](image)

The mechanical properties of composite materials used in the present study are described in Table 2.

### Tables 2. Mechanical properties (bending test result).

| Properties         | Experimental | Theoretical | Perc. | Error% |
|--------------------|--------------|-------------|-------|--------|
|                    | RMGF         | MWGF        | RMGF  | MWGF   | RMGF | MWGF |
| Elasticity modulus | 2.9          | 2.6         | 2.96  | 2.7    | 2.07 | 3.84 |
| Flexural, MPa      | 84.4         | 80.6        | 88.4  | 82.6   | 4.73 | 2.48 |
| Fracture, MPa      | 46.7         | 41.2        | 51.3  | 46.8   | 9.85 | 13.5 |
| Strain (%)         | 13.8         | 13.3        | 14.3  | 14.1   | 2.17 | 6.01 |

The percentage error between the experimental and theoretical results shows acceptable values between 13.5% and 9.85% from the comparison between MWGF and RMGF for flexural strength and 6.01% and 2.17% for strain, respectively.

### 4.3. Impact test results

Table 3 shows the amount of strain energy and deformation during the impact test. It seems clear that the ability of the suggested composite material to withstand the deformation and strain energy. The experimental work indicates acceptable results with 24.56% and 7.80% error percentage from the comparison between RMGF and MWGF for strain energy and 17.2% and 4.82% error percentage for deformation, respectively.

### Tables 3. Mechanical Properties (impact test result).

| Properties         | Experimental | Theoretical | Perc. | Error% |
|--------------------|--------------|-------------|-------|--------|
|                    | RMGF         | MWGF        | RMGF  | MWGF   | RMGF | MWGF |
| Str.Energy,MJ      | 22.64        | 19.85       | 28.2  | 21.4   | 24.56 | 7.80 |
| Defor., mm         | 3.14         | 3.1         | 3.68  | 3.25   | 17.2 | 4.82 |
Finite Element Analysis (FEA) was used to simulate the impact test outputs, as shown in Figure 7 and Figure 8 for the obtained deflection results.

5. Numerical simulation results

The analytical solution for the full car roof modeling gives acceptable results for displacement and stress distribution based on Von-misses theory. Figure 9 and Figure 10 show displacement distribution, and Figure 11 and Figure 12 show the stress distribution.
6. Conclusion
The main conclusions of the present work, which is based on the investigation of tensile, flexural, and impact analysis of composite material, are as follows:

- Milled waste glass fiber with a volume fraction of 14% showed acceptable young modulus, maximum stress, yield strength, and strain energy when compared with the random mate glass fiber.
- Milled waste glass fiber composites may be considered one of the promising candidates to be used for the car roof structure where high stiffness and fracture resistance are required.
- The theoretical solution and response of the full car roof structure refer to a compatible solution for displacement and stress results.

The milled waste glass fiber could be considered as an excellent reinforcement and filler material that verify the economic aims, especially where it has a weight effect of the total composite material. Also, it verifies the environmental aims, which is represented by the disposal of waste material as it needs several decades to be biodegradable and converted to useful material. The free cost waste makes the suggested material is a good alternative one, in addition to disability comparison between it and a standard one that manufactured by specific companies because of the lack of information about the know-how of these companies.

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