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Utilizing factorial modeling to probe multifaceted mechanical properties of polymer composites

Polimer kompozitlerin çok yönlü mekanik özelliklerini araştirmak için faktöriyel modellemenin kullanilmasi

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Utilizing Factorial Modeling to Probe Multifaceted Mechanical Properties of Polymer Composites

Highlights

- ❖ *Thorough materials research is indispensable for intricate aerospace design.*
- ❖ *Innovations in materials are overriding to meet stringent aerospace design specifications.*
- ❖ *Material advancements do not obviate the necessity for comprehensive testing.*
- ❖ *Accurate monitoring of material properties is essential in aerospace design.*
- ❖ *Utilizing factorial modeling improves the accuracy of mechanical property analysis.*

Graphical Abstract

In this study, the two-factor analysis of variance methodology is used to effectively explore the interrelations among the two main mechanical properties. The methodology helped to identify the statistical relations among mechanical properties of various composite specimens. The case of replications of the treatment combinations determined by the levels "CFE1", "GFE1" and "CFE2" of factor "Specimens" and different combinations of the levels "UTS (MPa)", "ILSS (MPa)", "FS (MPa)", "YM (GPa)", "TM", and "PR" of factor "Properties" are used accordingly. The result of the experimental analysis showed us that the two factors (main effects) and the interaction are significant.

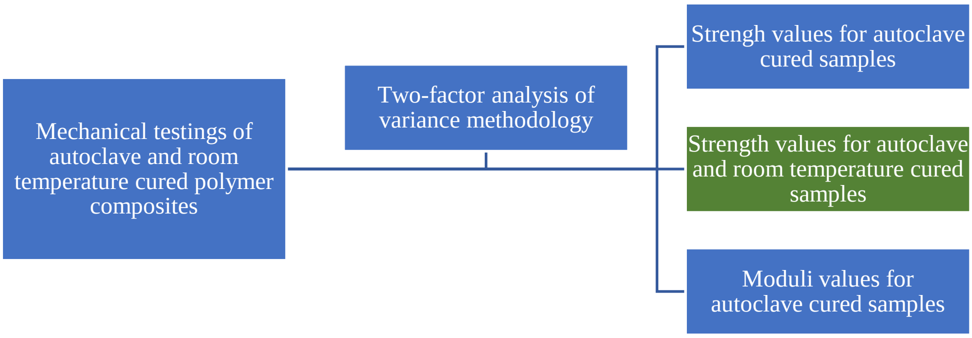

Figure. Prompt visualization of steps undertaken in the study

Aim

The aim is to contribute to aerospace design by conducting materials research and employing factorial modeling to analyze mechanical properties accurately.

Design & Methodology

The objective is to explore elastic and strength properties of epoxy/fiber composites using the factorial design method, allowing for comprehensive analysis of statistical relations among interlaminar shear strength, flexural strength, and tensile properties, which surpass other parametric and nonparametric testing approaches.

Originality

Employing averaged values alongside statistical evaluations to address concerns regarding reusable parts and crashworthiness in aerospace, while factorial analysis explores key mechanical properties prior to safety and sizing assessments.

Findings

The effective exploration of interrelations among the principal mechanical properties demonstrated by samples is achieved through the application of factorial analysis methodology.

Conclusion

The utilization of averaged values alongside detailed statistical evaluations, coupled with factorial analysis, offers a promising approach for addressing concerns related to reusable parts, crashworthiness, and safety assessments in aerospace engineering.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Utilizing Factorial Modeling to Probe the Multifaceted Mechanical Properties of Polymer Composites

Araştırma Makalesi / Research Article

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ABSTRACT

Design tasks involving multiple complex requirements and constraints reveal the need for extensive materials research in the aerospace industry. This situation emphasizes the necessity for innovatively developing materials that conform to structural design specifications. However, reasons given for the advancement of materials neither abolish material testing requirements nor supersede simplified design approaches. Moreover, in structural design processes, particularly with composite materials, there is a critical need for meticulous examination of elastic and strength properties. Therefore, this study evaluates the tensile, flexural, and interlaminar shear properties of various composite materials, tested according to relevant ASTM standards, using a two-factor analysis method. The analysis of elastic properties in glass fiber and carbon fiber reinforced laminates considers elastic modulus, tangent modulus, and Poisson's ratio, while strength properties are evaluated based on interlaminar shear strength, three-point bending strength, and tensile strength. This comprehensive approach ensures a detailed analysis of all possible combinations of factor levels. Factorial modeling is proposed as a useful method while performing analysis on the mechanical properties rather than roughly providing averaged values for the tested materials.

Keywords: Aerospace structures, polymer composites, mechanical testing, statistical analysis, two-factorial analysis.

Polimer Kompozitlerin Çok Yönlü Mekanik Özelliklerini Araştırmak için Faktöriyel Modellemenin Kullanılması

ÖZ

Havacılık endüstrisinde çoklu karmaşık gereksinimleri ve kısıtları içeren tasarım süreçleri, kapsamlı malzeme araştırmalarının yapılmasını gerektirmektedir. Bu durum, yapısal tasarım özelliklerine uygun malzemelerin yenilikçi bir şekilde geliştirilmesini ortaya koymaktadır. Ancak, ileri malzeme araştırmalarını gerekli kılan bu nedenler ne malzeme test gereksinimlerini ortadan kaldırmakta ne de basitleştirilmiş tasarım yaklaşımlarını geçersiz kılmaktadır. Bununla beraber, yapısal tasarım süreçlerinde, özellikle kompozit malzemelerin elastik ve dayanım özellikleri hassas bir şekilde incelenmelidir. Dolayısıyla bu çalışmada farklı kompozit malzemelerin ilgili ASTM standartlarına göre test edilen çekme, eğme ve tabakalar arası kayma özellikleri, iki faktörlü analiz yöntemiyle değerlendirilmiştir. Cam elyaf ve karbon elyaf takviyeli tabakalı kompozitlerin elastik özelliklerinin korelasyonunda elastik modül, tanjant modülü ve Poisson oranı dikkate alınırken dayanım özelliklerinin korelasyonunda tabakalar arası kayma dayanımı, üç nokta eğme dayanımı ve çekme dayanımı göz önünde bulundurulmuştur. Böylece, faktör seviyelerinin tüm olası eşleşmeleri için detaylı bir analiz sağlanmıştır. Test edilen malzemelerin aritmetik ortalama değerlerinin listelenmesinden ziyade mekanik özellikler üzerine çok yönlü analiz yapılması için faktöriyel modelleme kullanışlı bir yöntem olarak önerilmektedir.

Anahtar Kelimeler: Havacılık yapıları, polimerik kompozitler, mekanik testler, istatistiksel analiz, iki-faktörlü analiz.

1. INTRODUCTION

The utilization of composites in aerospace structural components has resulted in significant weight advantages over various engineering materials [1]. Structural segments such as fairings, engine casings, and inter-stage structures are fabricated using various manufacturing techniques like additive manufacturing, filament winding, fiber placement, or manual lay-up with composite prepregs or cellular/sandwich composite structures [2-5]. Traditional sizing methods for these structures maintain the ultimate load threshold before any damage occurs and account for manufacturing and operational defects with detrimental effects on composite material characteristics to validate the damage tolerance [6,7]. The influence of defects such as dimples needs to be assessed within the applicable range of the structure. Suitable methodologies could be integrated by considering damage effects to ensure optimal sectional and dimensional parameters for prompt sizing issues encountered during a typical design cycle [8-10].

Aerospace structures such as fan blades, fuselage, and wing sections, typically manufactured from metallic materials, benefit from comprehensive analysis techniques like finite element analysis [11]. Recent advancements have introduced innovative reduction techniques, refining the process to incorporate three-

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dimensional beam elements and shell elements [12]. Metallic materials are easily discernible due to their inherent homogeneity and isotropy. However, composites, comprised of fibers and matrix in varied orientations, lack the homogeneity and isotropy of metallic counterparts [13-15]. While design methodologies have traditionally relied on layered models assuming homogeneity, each layer adds to the material's anisotropy through its thickness. The strength of composite layers hinges on factors like fiber volume fraction and orientation, necessitating a bridging of the gap between averaged properties and computational structural analysis, ideally through detailed statistical analysis.

Statistical examination of the mechanical characteristics of composites is widely utilized in aerospace applications [16, 17]. It would be used either to reveal reliable combinations of reinforcement phase and matrix or to propose a determination of damage tolerance and repair design allowable value [18, 19]. The wide range of applicability of statistical methods provides researchers with valuable outcomes while performing typical structural design and analysis of an aerospace structure. However, a comparative examination of the strength and stiffness properties of glass fiber and carbon fiber reinforced composites is not commonly studied using factorial modeling. The impact of a variable in a factorial design is the alteration in response brought about by any modification within the acquired experimental outcomes associated with the variables. By using factorial design, it is possible to reveal the individual main effect behavior in addition to the interactional behaviors of the factors very accurately. They provide additional information and have solutions to the drawbacks of one-factor-at-a-time methods. Especially, when there exist interactions, it is better to use factorial modeling to avoid being misled or following incorrect decisions. Except for providing additional information about the interactions, the factorial designs enable one to understand the behavior of a factor to be seen at different levels of the other factors [20]. Causeur et al. [21] developed a model for the investigation of the interaction by using two-way analysis of variance models for homologous factors. The study is proposed a model for interaction between homologous factors which includes procedures for the impacts of each extent in the interaction.

Factorial modeling of experiments provides information on the interaction effects between properties and specimens, it would be preferred over other one-to-one parametric or nonparametric methods such as one-way ANOVA test, Kruskal Wallis test, two-sample t-test, and two-sample Kolmogorov Smirnov test [22-28]. In this study, the elastic and strength properties of various epoxy/fiber composites are explored using two different strain measurement methods available in contact and non-contact modes. When obtained stress and strain data, the factorial design method is used to examine the statistical relationships between interlaminar shear strength, flexural strength, and tensile properties of composite samples. By using the factorial design methods, it would be possible to search for all possible combinations of the levels of the factors through each complete experiment or replication effectively.

2. MATERIAL and METHOD

2.1. Materials

Unidirectional glass fiber and carbon fiber reinforced composite samples are fabricated using room temperature curing and autoclave curing according to the manufacturer's recommended cure cycle. Those materials are certainly embedded in various aircraft components manufactured by Vestel Defence (Ankara, Turkey) and Epsilon Composites (Ankara, Turkey) as represented in Table 1. Due to the concern of these part manufacturers, further details are given in reference [29].

Table 1. Samples used in the study

Sample Code	Specimen Name	Fabrication Method	Part Manufacturer
CFE1	Carbon fiber reinforced epoxy composite	Autoclave cured	Epsilon Composties
GFE1	Glass fiber reinforced epoxy composite	Autoclave cured	Epsilon Composites
CFE2	Carbon fiber reinforced epoxy composite	Room temperature cured	Vestel Defence

2.2. Mechanical Testing

Quasi-static mechanical loading is convenient by following ASTM standards in order to examine how composite coupons react to subjected loadings. The aim behind these mechanical tests is to determine whether the coupons fit for purpose or not. The required information with regard to performing within design requirements is considered as the primary mechanical properties of the material. In order to examine these properties, mechanical tests are introduced with required ASTM test standards in the frame of D3039, D790, and D2344.

To assess the tensile properties of composite samples, ASTM D3039 serves as the benchmark, facilitated by a sophisticated non-contact digital image correlation (DIC) system. Data collection is conducted through a computer-controlled axial/torsional servo-hydraulic machine, specifically the MTS 809 model from the USA, equipped with a two-dimensional digital image system by Correlated Solutions Inc. (Figure 1). This DIC system is equipped with a high-speed camera, the GOM Inc. ARAMIS 4M from Germany, capturing five images per second at a resolution of 2358 x 1728 pixels. The camera, complemented by Titanar lenses with a 100 mm focal length, is mounted on a tripod with an inbuilt spirit level to ensure precise horizontal adjustment.

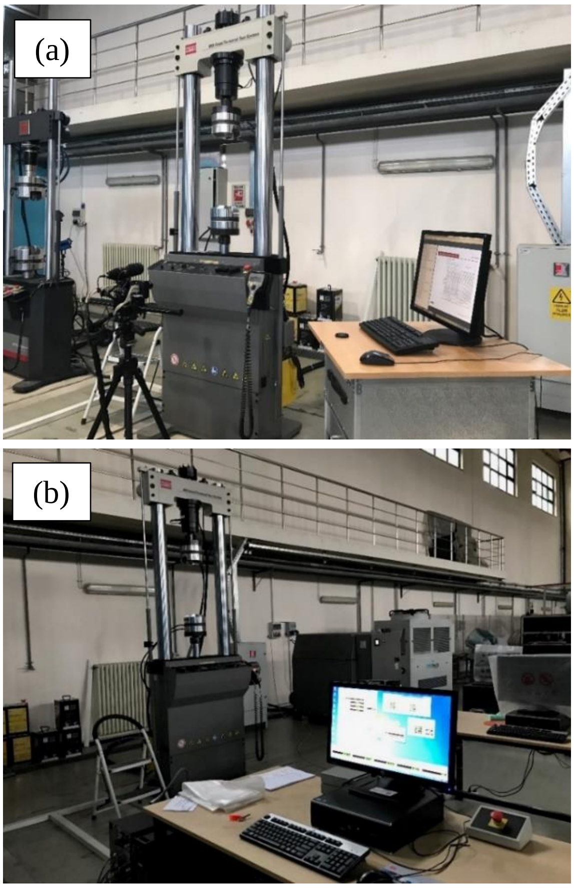

Figure 1. MTS 809 axial/torsional test machine with (a) DIC set-up and (b) user interface for MTS

To generate random speckle patterns on each specimen's surface, a technical black aerosol color, Graphit 33 from Kontakt Chemie Inc. in Germany, is sprayed over a previously applied white aerosol color, Art RAL 9010 from Dupli-Color Inc. in the USA, prior to testing. The colored surfaces are then compared with the Spray Pattern Reference of ARAMIS 4M provided by GOM Inc. (Figure 2). Subsequently, specimens are meticulously aligned and secured in hydraulic wedge grips. Uniform illumination of the specimen surface is achieved by placing two standard halogen light sources on each side of the camera setup. Calibration of the camera is ensured through a calibration grid plate, with captured images processed using ARAMIS Professional Software by GOM Inc. on a workstation computer. Tests are conducted at room temperature, with the cross-head speed adjusted to 2 mm/min in accordance with ASTM D3039 specifications. Additionally, hydraulic wedge grips are affixed, and torsional torque is zeroed. The strain field measurements obtained allow for the collection of stress (in MPa), longitudinal strain (in mm/mm), and lateral strain (in mm/mm) for each specimen.

Figure 2. The colored test specimens for DIC (carbon fiber at above and S-glass fiber at below)

A computer-controlled, screw-driven universal testing machine (MTS Model 45, USA) is equipped with a 100 kN load cell at a speed of 2 mm/min and 1 mm/min for D790 and D2344, respectively (Figure 3). The flexural strength of the test samples is the stress on the surface at failure which is associated with the breaking of fibers. The value of flexural strength is calculated by using the maximum bending moment formula. The thicker specimens are not suitable for D790 due to the elimination of significant sink marks or bubbles during the molding process. A support span to depth ratio of 16:1 is deemed appropriate for composites with a tensile strength to shear strength ratio of less than 8 to 1. However, this ratio could be adjusted upwards for high-strength reinforced composites with comparatively lower shear strength within the laminate plane and higher tensile strength parallel to the support span. The preferred dimension for the support span to depth ratio could be increased to 32:1 or 40:1. Therefore, the distribution of normal stress is viewed as linear, starting from a peak in compression on one surface to an equivalent peak in tension on the opposite surface, with zero stress occurring at the midpoint. The graph of shear stress is parabolic and it performs its maximum value at the neutral axis and a value that is equal to zero at the outer surfaces of the test piece. Interlaminar shear strength (ILSS) indicates the shear strength of adjacent layers in the laminate. D2344 test consists of three-point bending to produce interlaminar shear failure on a short-beam specimen in a horizontal direction. The load increases proportionally until the maximum load is achieved and the test is continued until failure occurs. After this point, the applied load drops significantly, immediately after the maximum load which causes the interlaminar shear failure.

2.3. Factor Analysis

The analysis of the variance method with two factors is employed to examine the statistical relationships among mechanical characteristics across different composite samples [30-32]. Replicated data is available for each combination of factors, such as the levels "CFE1", "GFE1", and "CFE2" of the "Specimens" factor, and various combinations of levels including "UTS (MPa)", "ILSS (MPa)", "FS (MPa)", "YM (GPa)", "TM", and "PR" of the "Properties" factor. The number of specimens outlined in corresponding ASTM standards constrains the replication count. Observations are organized in a rectangular array, with rows representing "Specimens" levels and columns representing "Properties" levels. Each combination of observations occupies a cell in this design.

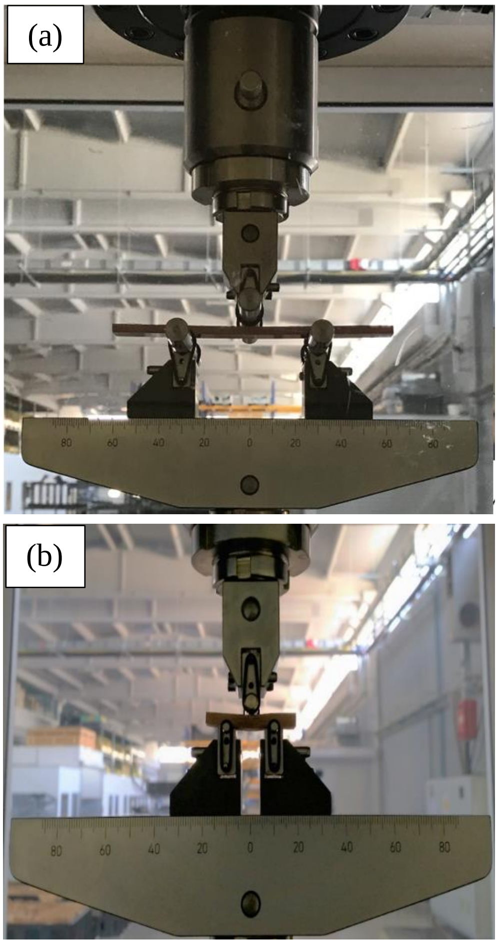

Figure 3. MTS 45 electromechanical universal test machine for (a) flexural test, (b) ILSS test

For every "Specimens-Properties" combination, there are "Specimens" times "Properties" levels of cells, each containing 'n' observations. If denoting the k^{th} observation at the i^{th} "Specimens" level and the j^{th} "Properties" level as y_{ijk}, the basic model for the two-factor design is expressed as

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{ijk}$$

Where $(\alpha\beta)_{ij}$ represents the interaction effect between the i^{th} level of "Specimens" and the j^{th} level of "Properties", α_i is the effect of the "Specimens", β_j the effect of the j^{th} level of "Properties", μ is the overall mean [20, 33].

It is assumed that the populations considered are the combinations of "Specimens" and "Properties" factors of interest, with the number of replications being independent and identically distributed observations. Moreover, an equal number of 'n' replications of observed responses are included in each factor combination [20].

3. RESULTS AND DISCUSSION

Three different groups of composite samples are tested using MTS universal test machines. Failure pictures are taken of the CFE1 and GFE1 samples (Figure 4), revealing distinct failure modes and deformation characteristics across the composite groups, thereby offering valuable insights into their mechanical behavior under tensile load. Subsequent to mechanical tests, comprehensive results are compiled, including ultimate tensile strength (UTS), Young's modulus (YM), Poisson's ratio, flexural strength (FS), and interlaminar shear strength (ILSS), as detailed in Table 2. The main effects and the interaction effects for the three alternative test combinations are evaluated by using factorial modeling accordingly. Strength data that cover flexural, ultimate tensile, and interlaminar shear strength of CFE1 and GFE1 specimens are referred to in the first case of factorial modeling. In the second case of factorial modeling, interlaminar shear strength and flexural strength data that belong to all three groups of specimens are used due to the availability of test results. In order to evaluate the stiffness relations for CFE1 and GFE1 specimens, Young's Modulus, Tangent Modulus of Elasticity, and Poisson's ratio are tested together in order to interpret the relations via statistical analysis among those properties.

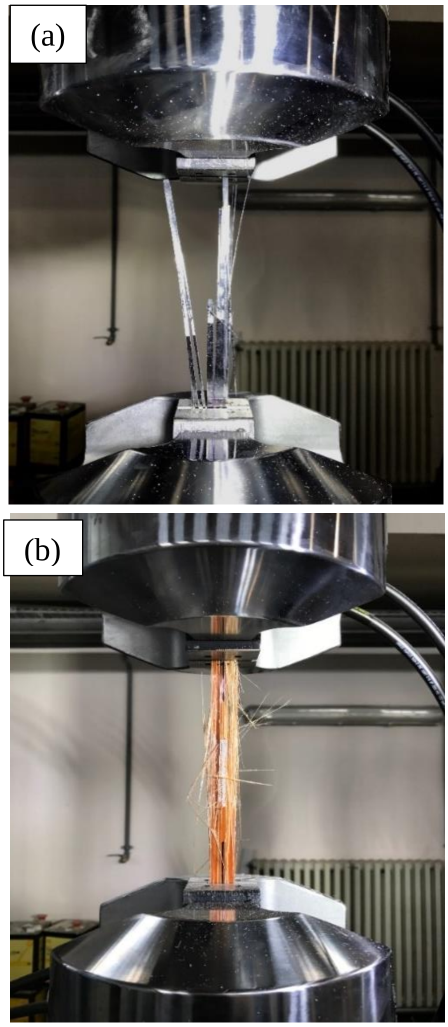

Figure 4. Failure image for composite test coupons tested with MTS 809 (a) CFE1, (b) GFE1

Table 2. Experimental test results for the mechanical properties of prepared composite samples

Mechanical property	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)	Poisson's ratio	Flexural Strength (MPa)	Tangent Modulus of Elasticity (GPa)	Interlaminar Shear strength (MPa)
Property code used in factorial modeling	UTS	YM	PR	FS	TM	ILSS
Autoclave cured Epoxy/carbon fiber (CFE1)	1735.56 ± 50.49	134.17 ± 2.64	0.3128 ± 0.00815	1968.53 ± 69.95	77.05 ± 3.21	115.88 ± 12.85
Autoclave cured Epoxy/glass fiber (GFE1)	1276.73 ± 51.61	45.05 ± 0.14	0.3214 ± 0.0096	1435.36 ± 43.95	42.33 ± 0.75	82.91 ± 2.87
Room temperature cured Epoxy/carbon fiber (CFE2)	NA	NA	NA	1009.52 ± 21.71	70.60 ± 3.29	17.93 ± 0.62

NA: No samples are tested using DIC setup system

Three hypotheses are tested as follows by way of hypothesis testing:

$H_0: \alpha_i = 0 \; for \; all \; i$ (Specimens)
$H_0: \beta_j = 0 \; for \; all \; j$ (Properties)
$H_0: (\alpha\beta)_{ij} = 0 \; for \; all \; ij$ (Specimens-Properties)
$H_1: \alpha_i \neq 0 \; for \; all \; i$ (Specimens)
$H_1: \beta_j \neq 0 \; for \; all \; j$ (Properties)
$H_1: (\alpha\beta)_{ij} \neq 0 \; for \; all \; ij$ (Specimens-Properties)

For each of these cases, the two factors "Specimens" and "Properties" are considered for the determination of a significant effect on the response behavior while searching if there is a significant interaction between these two factors [34-36]. The main factors, "Specimens" and "Properties" are the main effects. If the interaction "Specimens- Properties" is not significant, there exists evidence that hypothesis tests on the main effects are meaningful.

Firstly, experimental results for the mechanical properties UTS(MPa), ILSS(MPa), and FS(MPa) of prepared test specimens CFE1 and GFE1 in Table 2 to be tested by using data analysis tool of Excel Solver for two-factor variance analysis. According to the results in Table 3, for the "Specimens" and "Properties" main effects and "interaction" effect the null hypothesis is rejected because the P-values of all of the effects are smaller than the significance level of 0.05. Besides, the F-values are greater than the F-critic values which proves the significance of the main and the interaction effects. That means all of the "main effects" and the "interaction effect" affect the response for the mechanical properties UTS(MPa), ILSS(MPa), and FS(MPa) of prepared test specimens CFE1 and GFE1. For the second two-factor analysis of variance results stated in Table 2, the experimental results for the mechanical properties ILSS(MPa) and FS(MPa) of prepared test specimens CFE1, GFE1, and CFE2 are tested as well.

Table 3. Two-factor analysis of variance for factor "Specimens" (CFE1, GFE1) and "Properties" (UTS(MPa), ILSS(MPa), and FS(MPa))

ANOVA

Source of Variation	SS	MS	F	P-value	F crit
Specimens	558517	558517	197.0784	$8.2\text{x}10^{-9}$	4.747225
Properties	9149778	4574889	1614.296	$2.58\text{x}10^{-15}$	3.88529
Interaction	225285.2	112642.6	39.7471	$2.58\text{x}10^{-6}$	3.88529
Error	34007.81	2833.98			
Total	9967588				

Table 4 summarizes the results of the two-factor analysis "Specimens" and "Properties" main effects and "Interaction" effect. Accordingly, similar to the previous design for the "Specimens" and "Properties" main effects and "interaction" effect, the null hypothesis is not rejected because the P-values of all of the effects are greater than the significance level of 0.05. And, again similarly the F-values are smaller than the F-critic values that consolidate the insignificance of the main and the interaction effects. For this design, none of the "main effects" and the "interaction effect" affect the response for the mechanical properties ILSS(MPa), and FS(MPa) of prepared test specimens CFE1, GFE1, and CFE2.

Table 4. Two-factor analysis of variance for factor "Specimens" (CFE1, GFE1, and CFE2) and "Properties" (ILSS(MPa), and FS(MPa))

ANOVA

Source of Variation	SS	MS	F	P-value	F crit
Specimens	72572691	36286345	0.778181	0.466812	3.259446
Properties	5278129	5278129	0.113192	0.738492	4.113165
Interaction	1.12×10^{8}	56081278	1.202695	0.312166	3.259446
Error	1.68×10^{9}	46629687			
Total	1.87×10^{9}				

In the last case, the experimental results for the mechanical properties YM, TM, and PR of prepared test specimens CFE1 and GFE1 are tested. The results for the two-factor analysis "Specimens" and "Properties" main effects and "Interaction" effect are in table Table 5. Unlike the second factorial design, for the "Specimens" and "Properties" main effects and "interaction" effect the null hypothesis is rejected because the P-values of all of the effects are smaller than the significance level of 0.05. Additionally, the F-values have greater values than the F-critic values proving the significance of the main and the interaction effects. Hence, it is clear that the "main effects" and the "interaction effect" affect the response for the mechanical properties of YM, TM, and PR of prepared test specimens CFE1 and GFE1. Rejection of the null hypotheses for "Specimens" main effects implies that the response means (marginal means) at the levels of factor "Specimens" are significant. Additionally, a significant interaction needs an interpretation of designing new experiments to understand the effect of individual main effects on different fixed levels of the other effect. These evaluations would apparently be extended with the supply of more data combinations.

Table 5. Two-factor analysis of variance for factor "Specimens" (CFE1 and GFE1) and "Properties" (YM, TM, and PR)

ANOVA

Source of Variation	SS	MS	F	P-value	F crit
Specimens	4380.736	4380.736	804.5892	2.29×10^{-12}	4.747225
Properties	27519.67	13759.84	2527.204	1.77×10^{-16}	3.885294
Interaction	7561.645	3780.823	694.406	3.95×10^{-13}	3.885294
Error	65.33624	5.444686			
Total	39527.39				

4. CONCLUSION

Reasons for possible structural integrity losses like matrix fracturing, separation, and fiber rupture can result in a significant decline in mechanical characteristics and a weakening of resilience. Additionally, these impairments, which could inadvertently trigger eventual breakdowns throughout the operational life of a component/section, might spread even within customized composite formations and culminate in critical failures that could yield catastrophic outcomes. The characterization of composite materials at the coupon level not only by referring to averaged values but also supported by factorial modeling is proposed before performing damage assessments. Statistically uncovering connections between crucial mechanical properties would additionally influence the sizing process, aiming to boost structural performance while minimizing the risk of structural integrity compromise. A comparative analysis using factorial modeling would provide a useful evaluation regarding the extension of damage at the safety level.

The use of averaged values with detailed statistical evaluations is eminent in the aerospace field as growing interest focuses on reusable parts and crashworthiness issues. Before dealing with methodologies applicable to safety concerns and sizing issues, the interrelations among the main mechanical properties are effectively researched with the help of factorial analysis. In the second factorial design, none of the "main effects" and the "interaction effect" affect the response to the mechanical properties. However, for the first and the last designs, the "main effects" and the "interaction effect" affect the response to the mechanical properties. The response means (marginal means) at the levels of factor "Specimens" are found to be significant which reveals a significant interaction between the factors. The factorial modeling would be considered in order to associate the effect of individual main effects on different fixed levels of the other effect for further damage evaluations.

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in their study do not require ethics committee approval and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS

Hande GIRARD: Performed the experiments and analyzed the results. Wrote the manuscript.

Durdu Hakan UTKU: Performed the statistical methodologies using the experimental data and analyzed the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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