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The Reinforcement of Complete Upper Dentures with Not Widely Used Fibers in Dentistry Using a New Method of Incorporation

Efthymia Sklavou[1], **Anthony Prombonas**[1], **Aris Galiatsatos**[1], **Nikolas Poulis**[2]

[1]Department of Biomedical Sciences, Division of Dental Technology, School of Health and Care Sciences, University of West Attica, Athens, Greece; [2]Department of Dental Technology, Bolton University, Manchester, United Kingdom

Correspondence to: Anthony Prombonas, esklavou@uniwa.gr

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ABSTRACT

This study aimed to investigate the effect of new fibers not widely used in dentistry and hybrid fibers as reinforcing agents on fracture resistance of complete upper dentures (CUD). Five types of fibers (not widely used and hybrid fibers) were selected. Six groups of specimens were constructed, each with six identical samples. Specifically, one group served as the control group (no reinforcement), while the remaining five were reinforced with one fiber type per group. Fiber meshes were incorporated into the CUD specimens using a modified version of an established method, ensuring proper fixation and preventing slippage during compression into the flasks. Fracture toughness was measured using a Phywe, Universal Testing Machine, adapted to simulate masticatory loads experienced in the oral cavity. Statistical evaluation was conducted using ANOVA (Kruskal-Wallis) and Mann-Whitney test, while the reliability of the results was further analysed using the Wheibull method. Results showed that reinforcement of CUD with these fibers increased fracture strength, and the Weibull reliability of fiber-reinforced groups exceeded that of the control group. The study also highlighted the superiority of the Weibull method in evaluating the reinforcement effect compared to the non-parametric methods used.

1. INTRODUCTION

The need for improving the strength and longevity of prosthetic restorations was the primary motivation behind the development of dental biomaterials and the creation of appropriate procedures to enhance the durability of dental prostheses. This need for durable prostheses, led us to study the reinforcement of CUDs with hybrid fibers and other fibers that that are not widely used in dentistry. The estimation of the reinforcement could be evaluated through the measurement of flexural strength.

The complete denture of the upper jaw is most often fractured at the midline. This fracture is facilitated by fatigue during chewing, aging of the material due to temperature changes, and the chemical effects of saliva (e.g., enzymes), which result in increasing deformation over time [1].

Research conducted on the fracture resistance of CUDs shows that the upper complete denture is especially prone to midline fracture. For this reason, various researchers have tried to explain the causes and improve the material used to make complete dentures by reinforcing its mass with fibers. Despite these efforts, a complete solution has not yet been achieved, and the problem remains persistent in prosthodontics [2-4].

Important considerations during reinforcement include the exact positioning of fibers in the denture base and the volume of space they occupy.

Previous researchers have examined various fiber types, which, despite the advantages they offer, exhibit certain flaws that are outlined below:

- Nylon fibers, which tend to stain and absorb water rapidly.
- Polyethylene fibers, which are heat-sensitive.
- Kevlar and Carbon fibers, which affect aesthetics of the final restoration.
- Glass fibers, which show hydrolytic degradation over time [5-11].

With the aim of strengthening the bases of CUDs, this study chose to examine the contribution to the reinforcement of various types of fibers that have not been studied to date in the field of dental acrylic resin and the prostheses in the construction of which it participates.

This study's purpose was to investigate the use of new fibers not widely used and hybrid fibers in dental applications. The main objective was to examine the effect of incorporating meshes on the flexural strength of CUDs. Additionally, it tested a new method of fiber incorporation that ensures proper placement and prevents slippage. The study also analyzed the stress-strain curve of the specimens-complete dentures to investigate if this curve is similar to the strain curves of other structural systems-structures whether biological or mechanical.

More specifically, the fibers examined in the present study are:

- Innegra fibers: according to the manufacturer's manual, these fibers possess elasticity, tear resistance, low density, moisture resistance, excellent dielectric properties, durability, light weight, and stability at low temperatures. They are both chemically and biologically stable, highly crystalline, hydrophobic, resistant to elongation, and have microvoids in their structure. Additionally, they perform well in combination with other fibers and do not change color when wet [12-14].
- Diolen fibers: According to the manufacturer's manual, reinforcement with fibers of this kind typically provides superior impact and abrasion properties, combined with low density. These fibers can be used alone or in combination with other types of fibers in order to enhance impact resistance and elasticity [13].
- Vectran fibers: These fibers exhibit high strength and modulus of elasticity, excellent resistance to creep and impact, resistance to abrasion and tear, minimal moisture absorption (they are hydrophobic), chemical resistance, low coefficient of thermal expansion (they melt at high temperatures), high dielectric strength, and outstanding bending and vibration damping characteristics. Their molecules are rigid and organized into rod-like structures in ordered regions both in the solid state and in the molten state. This leads to anisotropies in the molten state. Finally, Vectran has good resistance to most acids and alkalis. The only notable exception is hydrofluoric acid, which can cause degradation of the fiber [15, 16].
- Glass & aluminium fibers: They are also known as Glare, and are used, among other applications, for coating the exterior surfaces of aircraft. These fibers provide properties such as high strength relative to their weight, long-term durability, high fatigue resistance, resistance to high temperatures, as well as resistance to crack propagation [17-19].
- Glass fibers: According to existing studies, despite their hydrolytic degradation over time, it has been demonstrated that glass fibers provide enhanced resistance to fracture [20-22].

2. MATERIALS AND METHODS

2.1. Specimens Preparation

Thirty-six specimens were fabricated to test the null hypothesis that reinforcing CUDs with lesser-known fibers would not increase their flexural strength. All specimens had the shape of identical complete upper dentures.

To incorporate fibers into the acrylic base, fiber meshes were first formed to match the shape of the denture. This was achieved by modifying the methodology of Prombonas *et al.* (2023) [23].

To modify the method, a 1 mm thick green wax sheet was placed on the study cast (initial cast), covering the labial and buccal sulcus, while a boxing strip was placed around the cast to pack putty silicone into the boxed cast (Turbosil Putty, R & S Co, Paris, France) (**Figure 1**).

Figure 1. Illustration of the boxed cast in order to fill in with silicone.

Once polymerized, the silicone was removed and its inner surface was coated with a thin layer of Vaseline. The silicone impression was boxed with boxed strip and putty silicone and was pressed with hands. This resulted in a two-piece mold consisting of silicone in both halves (**Figure 2**), where the lower half is the cast used in the present work slightly enlarged.

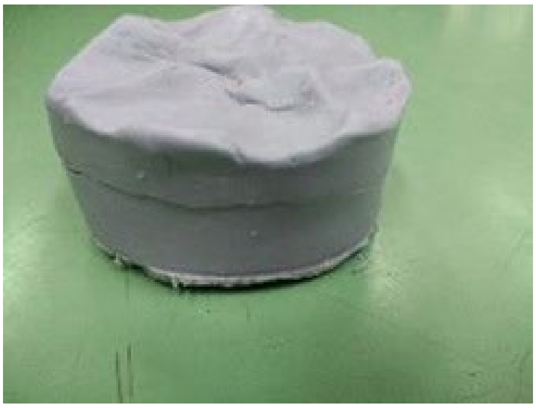

Figure 2. Two-piece silicon matrix.

The silicone matrix was flasked in the known manner (**Figure 3** and **Figure 4**) and thus a hybrid flask was obtained. Each one half of the flask consisted of the corresponding silicone half of the silicone mold, supported by gypsum, for reducing the deformation of silicone during pressing. Using this hybrid flask, it was easy to form the fiber meshes into the exact same shape [23].

Figure 3. **The silicone mold in the flask, first the lower half (left) and then the upper one. On the right, the opened hybrid flask.**

Figure 4. **The hybrid flask is opened, with a molded mesh ready to be incorporated into a complete denture.**

The incorporation of the fiber meshes into the CUD specimens was made following the methodology of an earlier study, which ensures the fixation of the fibers and the avoidance of mesh slippage during compression into the flasks [23].

Finally, the dentures were processed as usual (grinding, polishing and polishing) according to the basic principles of manufacturing complete dentures (**Figure 5**). The acrylic dentures were finished according to standard finishing procedures for acrylic resin denture bases [24]. During the grinding and polishing of the acrylic resin dentures, their thickness was measured at seven points on both the labial (lateral incisors' region) and buccal flanges (first molars' region), as well as on the palatal midline, namely the second molar region, the first premolar region, and the anterior region. These measurements were made using an analog thickness gauge with 0.1 mm precision (K series, Schmidt Control Instruments, Waldkraiburg, Germany) to ensure that the bases of all the denture specimens had the same thickness (3.0 ± 0.1 mm) [25, 26].

Figure 5. **Representative CUDs from the five groups of fibers ready for testing.**

More specifically, the following six groups of specimens were constructed:

1) Control group (no fiber).

2) Reinforced with Glass woven fibers (SILICA (Silicon Dioxide) (Glass EC9 68 Z28 876s)): 201 g/m^2.

3) Reinforced with Innegra woven fibers (Innegra S (S940 Innegra fiber)): 200 g/m^2.

4) Reinforced with Diolen woven fibers (DIOLEN (Diolen 164S fiber)): 200 g/m^2.

5) Reinforced with Vectran woven fibers (VECTRAN LCP (liquid-crystal polymer) (Vectran 1670 dtex)): 200 g/m^2.

6) Reinforced with Glass & aluminium hybrid woven fibers (ALUMINIUM & SILICA (EC9 68 tex fiber)): 520 g/m^2.

The following table (Table 1) summarizes the mechanical properties of the fibers used in this study [12-19, 27, 28].

Table 1. Mechanical properties of the fibers used in this study.

Fibers	DENSITY g/cm^3	TENSILE STRENGTH MPa	ELONGATION ON THE PERCENT %	STIFFNESS Modulus of Rigidity GPa	IMPACT RESISTANCE kJ/m^2	HYDROLYSIS ON THE PERCENT %
INNEGRA	0.84	700	9.5	15	3	<0.1
VECTRAN	1.41	3700 - 7400	3.3	22 - 25	16.6	<0.1
DIOLEN	1.38		10 - 16	7 - 8	Not available	Not available
GLASS	2.54	2600	5	72	2	0.1
GLASS & ALUMINIUM	2.44	3310	4.8	Not available	Not available	0.1

2.2. Flexural Strength Measurement

Flexural strength was measured using a Phywe, Universal Testing Machine, which applies tensile, compressive, shear, and bending loads. This machine was modified to simulate the forces exerted on CUDs during mastication in the oral cavity, following the methodology of a previous study. Each specimen (made from heat-curing acrylic resin) was subjected to compressive loading at a crosshead speed of 5 mm/min. These specimens (CUDs) were tested until fracture to obtain two values: 1. the load at which the complete upper dentures fracture (fracture load in kN), and 2. the amount of deformation-displacement at fracture (mm). These two values are recorded by a two-axis chart recorder device connected to the testing machine. Using these two values, a third value, the fracture energy, is calculated as the product of the load and the displacement, expressed in Joules ($J = N \times m$). The resulting load-specimen data allowed the assessment of fracture energy for each specimen group (Figure 6) [29].

3. RESULTS

Table 2 below shows only the fracture energy values for six specimens of each group tested in this study. These values were used to statistically evaluate the differences in fracture energy between the groups of the study.

3.1. Nonlinearity of the Load-Displacement Curve

A notable finding in this study was the nonlinear behavior observed in the load-displacement curves. This nonlinearity resulted from the custom loading method applied to simulate masticatory conditions within the oral cavity [29]. The following image (Figure 7) shows a typical load-displacement and fracture curve of the complete denture specimens of this study.

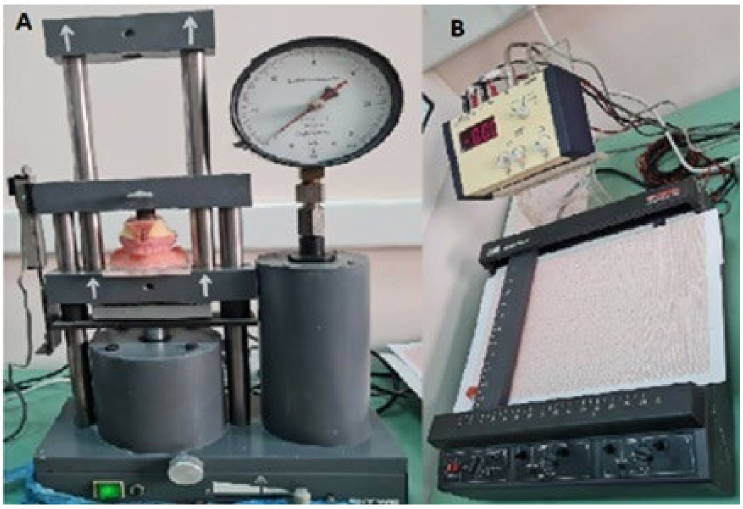

Figure 6. A Universal Testing Machine Phywe in operation and B. Load-displacement recorder attached to the testing machine [29].

Table 2. The fracture energy (Joules) values for six specimens of each category tested.

GROUPS	GROUP 1 Without Reinforcement	GROUP 2 Glass Fibers	GROUP 3 Glass & Aluminium Fibers	GROUP 4 Inegra Fibers	GROUP 5 Diolen Fibers	GROUP 6 Vectran Fibers
Specimen 1	16.28	16.77	24.28	12.52	26.208	14.8
Specimen 2	9.75	15.6	23.64	13.77	17.48	29.5
Specimen 3	4.57	15.88	24.40	16.11	13.99	25.3
Specimen 4	16.3	22.62	17.64	17.64	14.97	15.87
Specimen 5	13.94	14.68	17.51	9.93	13.87	15.02
Specimen 6	8.42	12.60	18.86	15.58	17.72	19.95
Mean Value	11.55	16.36	21.05	14.25	17.38	20.08

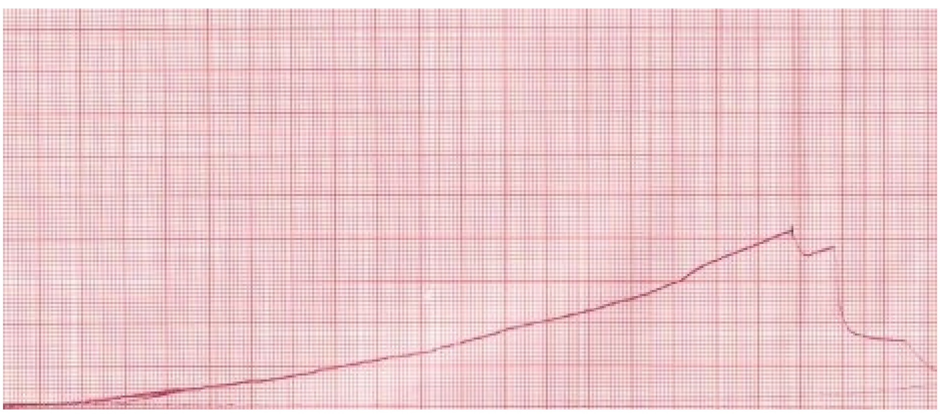

Figure 7. Nonlinear form of the load-displacement curve.

There are the following types of nonlinearities present in a system, which are responsible for changing the stiffness of a system during deformation [30].

1) Large deformations or geometric nonlinearity

2) Material nonlinearity

3) Contact nonlinearity

Nonlinearity can also arise when biological tissues interact with biomaterials through implants and medical devices [31, 32].

From a mechanical and material point of view, natural materials and tissues are composites, which, over thousands of years of evolution, are structured as "hierarchical" materials, that is, materials with a specific hierarchy in their structure, which leads to very efficient structures. Although these materials consist of relatively simple structuring blocks, their multi-layered structures and inherent structural patterns result in remarkable mechanical properties. Unfortunately, although the unique properties of soft fibrous tissues stem from their structural complexity, this complexity also hinders our ability to produce adequate synthetic analogs [33].

Understanding the structure-function relationship in these structures and mimicking them, it will revolutionize our ability to repair organs and tissues and restore the biomechanical function of native tissues. Furthermore, by using the same principles in applications of classical mechanics, we can take a new leap and revolutionize the next generation of materials [34-38].

Tendons and ligaments (important parts of the human body's support system) have a pronounced mechanical behavior with a J-shaped curve, with a very increased slope. Biomimetics is used to imitate natural mechanisms to develop newly designed materials with superior properties. According to the basic principles of Biomimetics, the basic parameters that control and influence the deformation and mechanical behavior of loaded fibrous structures of the human body (tendons, ligaments, artery walls, etc.) are: the fiber volume fraction (Fiber Volume Fraction_FVF), the fiber orientation, their recruitment to support loads during the strain of the fibrous structure, and the fiber crimping (Fiber Crimping) [34-38].

In addition to fiber orientation, volume fraction, and orientation, crimping also governs the mechanical behavior of soft tissues. The crimping of collagen allows an additional degree of freedom in the deformation of the material due to its ability to align under load, thus protecting the material from wear. The crimp structure has been divided into different structures, such as flat zigzag, sinusoidal or helical, with a wavelength range between 10 and 200 μm. Tendons and ligaments are composed of collagen fibers that follow a sinusoidal waveform along the tissue's length, called collagen fiber crimping. As these tissues are stretched, the folded fibers gradually align and support the load, which produces a nonlinear mechanical behavior. Because most tendons and ligaments experience loads in vivo in this nonlinear mechanical behavior, collagen crimping is believed to be an important structural feature underlying proper tissue function. This is further supported by the fact that collagen crimping changes with tendon injury, degeneration, and healing. Therefore, to fully replicate tendon/ligament structure-function relationships, engineered biomaterials that contain a similar crimping fibrous structure are needed [39, 40].

3.2. Statistical Analysis of Strength with Non-Parametric Methods

A statistical evaluation of the difference between the mean values of the strength of the various groups of complete denture specimens was performed. The box plot below (**Figure 8**) lists the summary statistics for the strength of the six categories of specimens-complete dentures that were studied and the level of statistical significance for both the variation of the mean values and the comparison of the mean values by pairs of the groups of specimens. Specifically, to study the variation between all mean values of the study groups, the Non-Parametric ANOVA Kruskal Wallis Test between K independent samples was used (since the denture specimens are different in each group), while to study the statistical significance of the difference between the mean values of all possible pairs of groups, the Non-Parametric Mann-Whitney test was used between all possible pairs of groups with independent samples (different specimens).

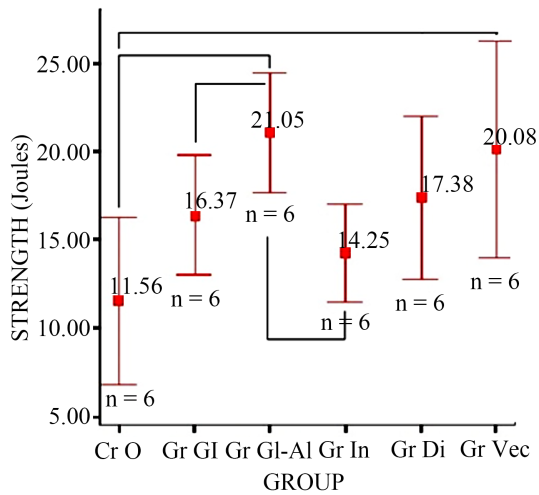

Figure 8. **Box plot showing the mean values of the flexural strength (in Joules) of the six categories of complete denture specimens and the range ± one SD. The black horizontal thin lines connect the mean values that showed a statistically significant difference, at a level of less than 0.05 ($P < 0.05$). Gr-Gl (Glass fobers), GrGl-Al (Hybrid mesh glass with aluminium), Gr In (Innegra fibers), GrDl (Diolen Fibers), Gr Vec (Vectran fibers).**

3.3. Statistical Analysis of Strength Data with the Weibull Method

Microsoft Excel and William W. Dorner's manual "Using Excel for Weibull Analysis" available on the Internet were used to analyze the flexural strength data of the tested CUD [41].

Figure 9 below shows the Weibull reliability curves of the six groups measured in this study. To create the reliability curves of the different test categories, the methodology proposed by Doner (2017) was followed using Microsoft Excel [41].

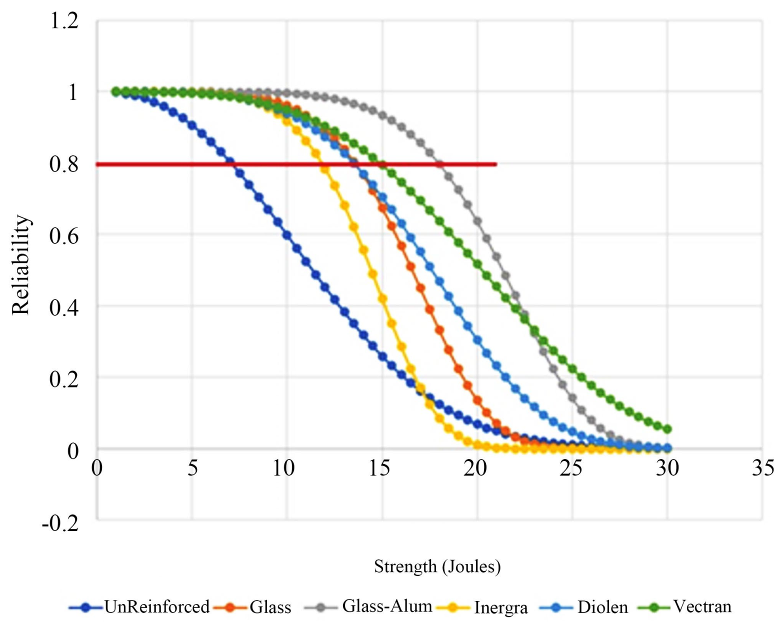

Figure 9. **Weibull reliability curves of the six groups studied in the present study. (blue = unreinforced, orange = glass, grey = glass-aluminium, yellow = innegra, light blue = diolen, green = vectran).**

4. DISCUSSION

All commonly used fibers in dentistry have notable disadvantages. More specifically, Nylon fibers quickly are stained and show a high water sorption. Polyethylene fibers are sensitive to heat, Kevlar and Carbon fibers show poor aesthetics of the final restoration and Glass fibers hydrolyze [5-11]. Especially Glass fibers which are the most used, are known to weaken when they are stressed in tension in the presence of water molecules on their surface. Glass fibers sensitivity to stress and moisture has been shown to be responsible for the dependence of the S-N curves in fatigue experiments on the frequency of the cyclic load, which is not found in carbon composites. The influence of hydrothermal ageing on the fatigue behavior and durability of unidirectional glass fiber reinforced polymers (GFRP) has been reported in a limited number of investigations. Moreover, glass-fiber composites in chemical plants and pipelines undergo chemical degradation [42].

This study examined the reinforcement of CUDs with fibers not widely used in dentistry and hybrid fibers, in order to study their flexural strength and deformation. The longevity and behavior of restorations, in addition to the correct design of the prosthetic restoration (avoiding stress concentration points), also depends on the good integration of the reinforcement into the acrylic mass. Since structural defects in lab-manufactured structures can act as stress concentrators, fracture due to flexural fatigue remains a risk during age [6-11, 22].

Regarding the strength of the complete denture specimens measured as work at fracture (in Joules), it is observed that all categories with fiber reinforcements presented an average value higher than the average value of the control group (no reinforcement).

With the non-parametric methods applied for the statistical evaluation of numerical data, a large variation is initially observed between the mean values of all categories (non-parametric ANOVA, Kruskal - Wallis $P = 0.016$).

As can be seen from the comparison of pairwise mean values with the non-parametric Mann-Whitney method, only the specimens reinforced with hybrid glass-aluminum (Glass-Al) mesh and Innegra mesh exhibited statistically significant higher mean values than the corresponding mean value of the control group of specimens without reinforcement. The remaining groups with mesh reinforcement exhibited higher mean values than the control group but not to a statistically significant degree. ($P > 0.05$). The results of this study agree with a large part of the corresponding research carried out in the past [5, 10, 21, 41, 43-48].

The evaluation of numerical data of flexural strength using the Weibull method showed that all reinforced groups of specimens, were more reliable than the control group of specimens (no reinforcement). It has been argued that comparing the mean values of two samples using parametric or non-parametric methods may not show a statistically significant difference, but the same values, if evaluated with the help of the Weibull distribution, can demonstrate and make this difference between the categories apparent [41].

According to the Weibull distribution data, when the parameter β (shape parameter) is greater than unity, this indicates an increased time horizon of failure, *i.e.*, it indicates wear failure, *i.e.*, after a long time of use. The same parameter indicates the nature, severity and dispersion of structural defects within a specimen or a structure. A high β value implies a uniform distribution of defects with high homogeneity and a small dispersion of strength values. Also, as the β value moves away from unity, the time horizon (fatigue time) of fracture failure increases [41, 49-54]. 48 - 53 From **Table 3**, it is observed that all groups with reinforcement of the specimens have a higher β value than the control group without reinforcement. This means that the time horizon of failure for all groups with reinforcement is removed in the following ascending order (longer service life in ascending order):

Table 3. Parameter alpha and beta from Weibull analysis.

	Unreinforced	Glass	Glass-Aluminium	Inegra	Diolen	Vectran
Beta (or Shape Parameter)	2.38	5.65	6.57	5.70	4.24	3.66
Alpha (or Characteristic Life)	13.2	17.69	22.58	15.37	19.21	22.39

Unreinforced (β = 2.38) < Vectran (β = 3.66) < Diolen (β = 4.24) < Glass (β = 5.65) < Innegra (β = 5.7) < Glass-Alum (β = 6.57).

An important issue highlighted by the present study and recorded mainly because a new loading method of CUDs was applied, is the nonlinear load-displacement diagram [29]. As previously stated and through Biomimetics, it was found that this curve is an open J curve, which is recorded in many parts of the human body during loading-strain, either the musculoskeletal system (ligaments), the circulatory system (walls of large vessels), or the muscular system (muscles and tendons), where loads and deformations develop. A common characteristic of all these parts of the human body is that they have a structure consisting of fibrils of constantly increasing size, which are interconnected either by the presence of an intermediate substance or through covalent bonds, and fibrils or fibers have a crimping structure. During the loading of these structures, there is a specific fiber reaction (reaction hierarchy) that begins with the alignment of the crimp and the sequential recruitment of different groups of fibers each time so that the fibers are initially directed towards the direction of the developing stresses, supporting a large part of the load and in a second phase the entire load. This fiber response to load makes these systems quite resilient and gives a J-shaped load-displacement diagram. The J-curve is characterized by an initially large displacement at low loads and then an increase in displacement with increasing load [31-34, 55].

The question arises is whether the structure of the CUD resembles the architecturally hierarchical structure of the crimping fibrils of biological systems described previously. The answer is probably positive. The CUD presents a folded hierarchical structure that starts from the crimping of the polymer macromolecules, the crimping of the fibers added for reinforcement and reaches the crimping of the outer surface of its base (curve shape), with the peculiar shape (shell shape) of the palate and flanges, that have to cover the ridges and the palate. To confirm the above, it is proposed to study the stress response of reinforced CUDs (e.g., under flexural loading), combined with microscopic observation of their internal structure before and after loading, using 3D CT (Computed Tomography). This approach aims to verify the above similarity based on the principles of biomimetics, with the ultimate goal of developing even more efficient composite materials and structures.

In addition, although the flexural strength assessment is valuable, additional mechanical tests like impact or fatigue testing could offer a more comprehensive understanding of the reinforcement effect.

Based on the literature accessible to us, only a few experimental studies mention the issue of fiber slippage during the flasking of acrylic resin. However, none report a specific percentage of the total number of specimens—CUDs in which this sliding phenomenon was observed [9]. In the present study, fiber slippage during acrylic packing was observed in five CUDs-specimens, corresponding to 13.8%.

5. CONCLUSIONS

The following conclusions emerged from this study:

1) It is observed that all categories with fiber reinforcements presented an average value higher than the average value of the control group, *i.e.*, the CUD without reinforcement. Among these, only the Innegra and hybrid Glass-Aluminum fiber groups exhibited statistically significant improvements according to Man-Whitney test ($P < 0.05$). The remaining groups with mesh reinforcement gave higher mean values than the control group but not to a statistically significant degree ($P > 0.05$).

2) The evaluation of numerical data of flexural strength using the Weibull method showed that all groups of specimens with reinforcement had better reliability than the unreinforced control group.

3) The failure possibility for all groups with reinforcement as it is represented by the shape parameter β, ranked the groups from least to most reliable as follows (longest life in ascending order): Unreinforced (β = 2.38) < Vectran (β = 3.66) < Diolen (β = 4.24) < Glass (β = 5.65) < Innegra (β = 5.7) < Hybrid Glass-Alum (β = 6.57).

4) The superiority of the Weibull method for evaluating the reinforcement with the selected fiber types was also emerged, compared to the non-parametric methods of Kruskal-Wallis and Mann-Whitney that were used for the same purpose and showed limited statistical significance (for some reinforcement groups).

5) The structural design of CUDs exhibits a biomimetic, crimped hierarchy-similar to biological systems like tendons and ligaments-which may contribute to their mechanical behavior. This structure starts from the crimping of the polymer macromolecules, the crimping of the fibers added for reinforcement and reaches the crimping of the outer surface of its base, with the peculiar shape that has to cover the ridges and the palate (curved, folded surface). During loading of the CUD in oral cavity conditions, these crimping structures initially partially straighten, so this corresponds to the first part of the curve where small loads cause large displacements. Subsequently, when the reaction is exhausted by straightening macromolecules or even the external shape, the remaining load is supported by the structure's shape.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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