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A Study on the Reinforced Properties of Dental Plastics with Hybrid Construction*

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Acrylic resin is widely used as the denture base material, but a failure of the upper complete denture often happens during its use. Therefore, the denture base made of acrylic resin should be reinforced by something else. So, the authors have thought of improving the strength and rigidity by laminating the organic fiber reinforced plastics on the palatal surface of the denture base, which is called the canapé construction. In this paper, the flexural strength, fatigue strength and the modulus of elasticity in bending of the canapé construction were investigated as basic experiment. As the result, the flexural and fatigue strengths have been improved to 160% and 130% of the denture base acrylic resin, respectively. And the modulus of elasticity in bending has been improved 80%. Therefore, it seems that this new combination of materials using the canapé construction might be applied well enough to the denture base.

1. Introduction

Acrylic resin is widely used as a denture base material in present dental clinic, but the upper complete denture base often fails during use, and it fails more frequently than the lower complete denture base⁽¹⁾. The reason for this phenomenon, as pointed out by many investigators, is the high tensile stress which develops along the mid-line in this construction when the biting force is applied to the complete denture base⁽²⁾. Therefore, so far, the denture base was reinforced by a metallic bar and a glass fiber, and discussion was made on these problems^{(3),(4)}. Recently, the chopped carbon fibers, with excellent mechanical properties, have been tried to improve the strength of the denture base resin⁽⁵⁾. But, these reinforcements used for the purpose of improvement of strength, were directly developed for dental use from the engineering side in which FRP structures are used as light weight structural components, and in the practical use with the patients, the irritation to the oral mucosa and the esthetics become a serious problem, and so the present problem lies in that these reinforcing methods of the denture base are not always good.

As a new reinforcing method of the denture base, we have tried to laminate the composite lamina on the palatal area of denture base, where the composite lamina consists of an organic fiber (Kevlar-49), which is recently attracting atten-

tion, with a high strength and modulus of elasticity as reinforcement, and a dental acrylic resin(PMMA) as matrix. Such a construction is the so-called canapé construction⁽⁶⁾, which is expected to improve the strength and stiffness, and this molding method can be treated in the same way as the present molding method at dental clinics. And from engineering aspect, recently it is attracting attention that the strength and the modulus of elasticity are improved by hybrid composite⁽⁷⁾, for example, a hybrid construction, which consists of CFRP lamination as facing and aluminium or GFRP as core^{(8),(9),(10)}. In this paper, as the basic experiments for the reinforcing method and the practical applications, we investigated the strength and rigidity of the canapé construction using the beam theory, and analytically studied the apparent modulus of elasticity and the flexural stress at facing and core for the laminated plate by the canapé construction, and the mechanical effectiveness of the reinforcement. And the canapé construction constituted of an organic fiber reinforced plastics and a dental resin was investigated by a statical flexural test and a flexural fatigue test. And the results of experiments were compared with the flexural properties of the non-reinforced dental resin used in general. They agree with the theoretical results.

Fig.1 Stress distribution in bending and dimension of canapé construction.

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2. Flexural stress and rigidity of the reinforced denture base resin

Fig.1 shows the canapé construction applied as the reinforcing method of the denture base, using acrylic resin (PMMA) for core material and a Kevlar-49 fiber reinforced acrylic resin (KFRP) for facing material. And the beam of the canapé construction, which is subjected to a uniform flexural moment, considering the mechanical properties of core and facing materials might be treated as the object of study when the tensile stress occurs to facing and the compressive stress occurs to core, and is expected to have mechanically excellent effectiveness. The maximum flexural stress σ_s produced at facing is represented using the apparent flexural stress $\sigma_{Hy}(=6M/bh^2)$ as follows:

$$\frac{\sigma_s}{\sigma_{Hy}} = \frac{(\alpha+1)^2(\alpha+1-\gamma)}{6\eta} \quad (1)$$

In the same manner, the flexural stresses σ_{c1} and σ_{c2} produced at the surface or the interface of core are as follows,

$$\frac{\sigma_{c1}}{\sigma_{Hy}} = \frac{-(\alpha+1)^2\beta\gamma}{6\eta} \quad (2 \cdot a)$$

$$\frac{\sigma_{c2}}{\sigma_{Hy}} = \frac{(\alpha+1)^2\beta(1-\gamma)}{6\eta} \quad (2 \cdot b)$$

where $\alpha = \frac{h_s}{h_c}$, $\beta = \frac{E_c}{E_s}$, $\gamma = \frac{h_0}{h_c}$,

$$\eta = \frac{1}{3}[(\alpha^3 + \beta) + 3(\gamma - 1)(\gamma(\alpha + \beta) - \alpha(\alpha + 1))]$$

And the coefficient γ is represented the rate between h_0 (the distance between the surface of core and the neutral axis) and h_c (the thickness of core) as follows.

$$\gamma = \frac{\alpha(\alpha+2)+\beta}{2(\alpha+\beta)} \quad (3)$$

Fig.2 shows the position of the neutral axis depending on the variation of the value of α using the equation (3), where the values of β are 1 and 0.167 ($E_c/E_s=317/1900$). As the value of α increases, the value of γ at $\beta=0.167$ exceedingly departs from a straight line at $\beta=1$ (where, $h_0=h/2$ = constant). And considering $\beta=0.167$ in this paper, in the region of $\alpha>0.412$, the value of γ is $\gamma>1$, therefore, as the position of the neutral axis is in the facing, only the compressive stress occurs in core

Fig.2 $\gamma - \alpha$ diagram.

part, and the compressive and tensile stresses occur in facing part. Therefore, the value of $\alpha=0.412$ for $\beta=0.167$ shows the critical point deciding the stress distribution, because only the compressive stress occurs in core part and only the tensile stress occurs in facing part. Fig.3 shows the $\sigma_s/\sigma_{Hy}-\alpha$ diagram using the equation (1), as shown in this figure, the flexural stress at facing σ_s is larger than the value of σ_{Hy} and is particularly high in the region of $0<\alpha<0.3$. This shows that the effectiveness of the canapé construction tends to appear when using a thin facing, although this effectiveness somewhat differs by the modulus of elasticity of laminated respective materials. And the flexural stresses at core σ_{c1} , σ_{c2} are shown in Fig.4. These flexural stresses show smaller values than σ_{Hy} as the value of α increases. This shows that the reinforced effectiveness has appeared by facing. And being more than $\alpha=0.412$, the compressive stress tends to occur at interface.

Then, the ratio of the apparent modulus of elasticity E_{Hy} in bending of the reinforced denture base resin to its value E_c of the non-reinforced denture base resin is represented as follows:

Fig.3 $\sigma_s/\sigma_{Hy} - \alpha$ diagram.

Fig.4 $\sigma_{c1}/\sigma_{Hy}, \sigma_{c2}/\sigma_{Hy} - \alpha$ diagram.

$$\frac{E_{Hy}}{E_c} = \frac{12\eta}{(\alpha+1)^3\beta} \quad (4)$$

Fig.5 shows the result of equation (4). The value of E_{Hy}/E_c rapidly increases in the region of $0 < \alpha < 0.2$. This shows that the property of the reinforced denture base resin has improved like the result of the stress in the region of the small value of α .

3. Specimen and experimental method

The specimen was made of the denture base acrylic resin plate ($h_c=2.5\text{mm}$) and the lamina ($h_s=0.5\text{mm}$) of organic fiber reinforced resin and has value of $\alpha=h_s/h_c=0.2$. The lamina (KFRP) consisted of a PMMA prepolymer as the matrix, BPO (benzyl peroxide) as the hardener and methyl methacrylate with 3% amine as diluent and the Kevlar-49 fiber cloth (style 180) having a thickness of 0.3mm as the reinforcement, and was made by the hand lay-up method at room temperature (molding pressure; 0.25 kg/mm^2) and then post-cured at 70°C for 12 hours.

Fig.6 shows the specimens for the three-point loading flexural test and fatigue test. Particularly, in the preparation of a fatigue specimen, after bonding a PMMA sample having the dimensions shown in Fig.6 to a long strip typed lamina, the specimen was cut to its dimensions by knife.

In the three-point loading flexural test the span is 60mm and the cross head speed is 2.5 mm/min . The fatigue test is carried out by a constant-stress typed fatigue machine (UF-15 Shimadzu Co.) with a repeating speed of 1800 rpm.

4. Result and discussion

4.1 Flexural properties

4.1.1 Flexural strength

Fig.7 shows the flexural stress-deflection diagram (σ - δ diagram) of PMMA, KFRP and the reinforced denture base resin, using one specimen each out of five specimens. The core part of KFRP-A is the compression side and the core part of KFRP-B

Fig.5 E_{Hy}/E_c - α diagram.

is the tension side. Only the KFRP specimen has a particular thickness of $h=1.5\text{mm}$, and the specimen consisting of a five-ply Kevlar-49 fiber cloth, therefore, its flexural rigidity and deflection can not be directly compared with those of other specimens. The flexural strength and the modulus of elasticity in bending of KFRP-A are improved more than PMMA and its flexural strength shows nearly the same value as KFRP. However, KFRP-B, of which the core is tension side, never shows an improvement of the flexural strength, and shows a decrease of the yield point. This shows that the efficient application of KFRP lamina is to use it as the tension side. And considering the deflection at the yield point, the deflection δ of PMMA at the yield point $\sigma_y=5\text{ kg/mm}^2$ is 3.15mm , but the result of KFRP-A, considering it has disappeared from the region of the linearity of the σ - δ relationship of KFRP-A when its PMMA part has reached the stress of $\sigma_y=5$

Fig.6 Flexural and fatigue specimens.

Fig.7 Flexural stress-deflection diagram. (loading span: $L=60\text{mm}$, thickness of KFRP plate: $h=1.5\text{mm}$)

kg/mm^2 , is obtained for $\delta=2.3\text{mm}$ (where $\sigma_{Hy}=7.1\text{ kg/mm}^2$) when using the beam theory, and has decreased comparing with the result of PMMA. However, as shown in Fig.7, the deflection of KFRP-A at the yield point is increased more than the calculated result, therefore, this shows that the linearity of KFRP-A is more superior. It is considered that the strain at core has been decreased because of the transverse restraint of the stress which occurs to core part owing to facing, and this shows that a characteristic of canapé construction has appeared. And KFRP-B occurred the yielded point at a small deflection comparing with KFRP-A. This result, as shown in the result of the compression test of Kevlar-49 fiber reinforced plastics ($\sigma_y=4.7\text{ kg/mm}^2$, $E=715\text{ kg/mm}^2$) which is explained after, is caused so that the compressive properties of KFRP are exceedingly worse than its tensile properties. As such a difference between KFRP-A and KFRP-B is due to the compressive properties of KFRP, considering the molding of the denture base and the efficiency of the tensile properties of KFRP, the canapé construction of which KFRP lamina is the tension side is an effective means in construction of denture base.

Table 1 shows the respective results of the three-point loading flexural test. The value of yield point σ_y of KFRP-A is 120% improved over PMMA, and the flexural strength and the modulus of elasticity in bending are increased about 160% and 80% respectively. Thus, these results show that the effectiveness of the canapé construction is obvious.

Table 1 Flexural properties of KFRP/PMMA canapé construction and PMMA, KFRP plates.

Specimen	σ_y kg/mm ²	σ_b kg/mm ²	E_b kg/mm ²
PMMA*	5.0	8.2	317
KFRP**	10.0	22.8	1900
KFRP-A	11.1	21.3	570
KFRP-B	3.7	7.8	544

* Denture base acrylic resin.

** Specimen of $h=1.5\text{mm}$ used. (Kevlar-49 fiber cloth style-180, 5-ply)

Table 2 Flexural strength and maximum flexural stress of facing and core parts at fracture point of canapé construction.

Specimen	$(\sigma_{Hy})_b$ kg/mm ²	σ_s^* kg/mm ²	σ_{c1}^* kg/mm ²	σ_{c2}^* kg/mm ²	E_b kg/mm ²	E_{Hy}^* kg/mm ²
KFRP-A	21.3	40.1	15.0	3.2	570	620
KFRP-B	7.8	14.7	5.5	1.2	544	620

* Calculated results.

Table 3 Ratio of improvement for canapé construction.

Specimen	$\sigma_s^*/(\sigma_b)_s$	$\sigma_{c1}^*/(\sigma_b)_c$	E_b/E_{Hy}^*
KFRP-A	1.759	1.829	0.919
KFRP-B	0.645	0.671	0.877

$(\sigma_b)_s, (\sigma_b)_c$: Flexural strength of facing and core.

Table 2 shows the flexural stress at fracture point occurring at facing and core part of KFRP-A and KFRP-B when using the equations (1) and (2), and also shows the modulus of elasticity in bending using the equation (4), respectively. In the results of KFRP-A, where the values of σ_s and σ_{c1} are larger than those of any other stresses, therefore, an excellent effectiveness of canapé construction is shown, because the mechanical properties of both materials of facing and core have been sufficiently displayed. But, KFRP-B does not display sufficiently the mechanical properties of both materials of facing and core, because the respective stress values of KFRP-B are very small.

Furthermore, about the modulus of elasticity in bending, its experimental values agree approximately with the calculated result, and this shows that the beam theory is sufficiently applicable. Table 3 shows the ratio of the stress at the fracture point obtained with each of the surfaces of the canapé construction to the flexural strength of these materials, and the ratio of experimental elastic modulus to calculated modulus, for KFRP-A and KFRP-B, respectively. Thus, the degree of the reinforced effectiveness is understood from these results. It seems that these calculated results obtained by the beam theory will somewhat differ from the true flexural stress near the fracture point under the assumption of the linearity of the flexural stress distribution, but, the flexural stresses for KFRP-A might be represented by high values owing to good bonding in the interface of the canapé construction. Thus, these results show that the properties of both materials constituting the canapé construction make a contribution to the strength and stiffness of its construction. And, the flexural stress at facing part shows a larger value than the flexural strength of only KFRP. The reason could be as follows: The fracture of KFRP under the three-point loading system is due to the local buckling fracture at loading point, therefore, its tensile property is not displayed, but the flexural stress at KFRP part of the canapé construction, which shows excellent properties, is only a tensile stress. Such a phenomenon is discussed by the tension and compression test for only KFRP sample, and the results obtained are shown in Table 4 and represented as the mean value of five specimens. The specimen of KFRP consists of a five-ply Kevlar-49 fiber cloth. The tension test is made according to ASTM D-638-68 and the compression test is made according to ASTM D-695-69. As shown in Table 4, the tensile strength is $\sigma_B=40.1\text{ kg/mm}^2$, therefore, this value is nearly equal to $\sigma_s=40.8\text{ kg/mm}^2$ of KFRP part of KFRP-A shown in Table 2. But,

Table 4 Results of tension and compression tests for KFRP plate.

Property	E kg/mm ²	σ_y kg/mm ²	σ_B, σ_c kg/mm ²
Tension	1720	23.5	40.8
Compression	715	4.7	7.4

in contrast with the tensile strength, the compressive strength is $\sigma_B = 7.4 \text{ kg/mm}^2$, and this value is very small and equal to 82% of the tension. These results show that the compressive properties of KFRP are not exceedingly good. Thus, the reason for the high flexural strength of KFRP-A is explained by these results obtained, and the applicability of the beam theory has been verified.

4.1.2 Fracture mode in bending the reinforced denture resin

Fig.8 shows the fracture modes in bending of PMMA, KFRP, KFRP-A and KFRP-B, respectively. The specimen of KFRP-A is broken into two pieces. The fracture mode of its core part differs from the fracture mode of PMMA and is a considerably complex fracture, resulting in a compressive stress. But, KFRP-B shows the same fracture mode as PMMA and the facing of KFRP-B is not broken. The specimen of only KFRP is not broken into two pieces, but its fracture is observed as a local buckling phenomenon at the loading point on the compression side.

4.2 Fatigue properties under pulsating plane bending

In the denture base, the compressive stress is considered to occur during use at the reverse side and the tensile stress at the right side. Therefore, in this paper considering such a practical use, the fatigue properties under pulsating plane bending might be investigated.

4.2.1 Stress amplitude - number of cycles to failure diagram (S - N diagram)

Fig.9 shows the S-N diagrams of PMMA and KFRP-A where the x mark shows an S-N diagram of PMMA and the o mark shows one of KFRP-A, the two other marks showing the stress which is produced on the surface or interface of core part when using the equations (2-a) and (2-b). As shown in Fig.9, the fatigue strength of the reinforced denture resin is very improved over that of only PMMA, and PMMA at core part shows an excellent property due to the canapé construction. And, the tensile stress at the interface of core σ_{c2} is very small, and

Table 5 Fatigue properties of canapé construction and PMMA plate.

Specimen	σ_{uf} kg/mm ²	σ_{uf}/σ_b	σ_{uf}/σ_y
PMMA	3.4	0.415	0.680
KFRP-A	7.8	0.366	0.703

Fig.8 Flexural fracture modes.

in contrast with this, though the compressive stress at the surface of core σ_{c1} is larger than the fatigue strength of only PMMA, the specimen of the canapé construction is not failed. Thus, the effectiveness of the canapé construction is understood.

4.2.2 Fatigue strength

Table 5 shows the fatigue limits under pulsating plane bending σ_{uf} of PMMA and KFRP-A, respectively. The fatigue limit is represented as the fatigue strength at $N = 10^7$ cycles. The fatigue limit of PMMA is $\sigma_{uf} = 3.4 \text{ kg/mm}^2$ and that of KFRP-A is $\sigma_{uf} = 7.8 \text{ kg/mm}^2$ and nearly 130% of that of PMMA. Thus, the effectiveness of the canapé construction is characterized by this result. Then, considering the ratio of σ_{uf} to σ_b or σ_y in the static properties, although the value of σ_{uf}/σ_y of KFRP-A is larger than that of PMMA, the value of σ_{uf}/σ_b is small, resulting in an increase of σ_{uf} and σ_b of KFRP-A over these values of PMMA. On S-N diagram, although it often happens that the fatigue strength in such a hybrid construction exceedingly decreases with an increasing number of cycles to failure, the fatigue strength of KFRP-A tends to decrease with an increasing number of cycles to failure in the same tendency as PMMA, and the fatigue strength of KFRP-A shows that it can be an excellent fatigue property. Therefore, the canapé construction reinforced with the organic fiber is likely to be applied sufficiently well as the denture base material when durability is required.

4.2.3 The fracture mode of the fatigue under pulsating plane bending

Fig.9 Stress amplitude-number of cycles to failure diagram.

Fig.10 Fatigue fracture modes.
(KFRP-A)

Fig.10 shows the fracture mode in fatigue of KFRP-A, where the fatigue failed specimen is broken into two pieces and is observed to peel off near the fracture surface of facing. It seems that such a peeling phenomenon results in poor mechanical properties of the matrix using only the dental acrylic resin considering the moldability and the ill effects. However, the characteristic failure of KFRP which locally occurs in bending is not observed either in fatigue, resulting in a tensile fracture of KFRP. This shows that the reinforcement assures the low tensile strength of the matrix and very much contributes to the improvement of the fatigue strength of the reinforced denture base resin.

5. Conclusions

Concerning the canapé construction (unsymmetrical lamination) reinforced with fiber reinforced lamina to one side of an acrylic resin plate used widely as the denture base material, the flexural and fatigue strengths have been investigated as the fundamental data on the practical use considering the material of construction, the molding technique and the esthetics as the denture base material. The results obtained are summarized as follows.

(1) The flexural stress and the apparent modulus of elasticity of the canapé construction which is subjected to a load in bending were analyzed using the beam theory. The results obtained show that the canapé construction with a comparatively thin facing shows exceedingly excellent properties. The mechanical properties of the canapé construction have a marvelous effect due to the ratio of the modulus of elasticity of facing to that of core.

(2) The property of dental acrylic resin (PMMA) as the matrix of composite material is not good comparing with industrial acrylic resin, and the flexural strength of organic fiber reinforced plastics (Kevlar-49 fiber/acrylic resin, KFRP) is 44% lower than its tensile strength and this result differs from the general composite materials. Therefore, KFRP is not used simply as the component in bending and found suitable for the use in such a canapé construction which makes the best use of the tensile property of KFRP.

(3) The fatigue limit under pulsating plane bending (fatigue strength at $N=10^7$) of the dental acrylic resin is $\sigma_{bf}=3.4 \text{ kg/mm}^2$, and the stress ratio of the fatigue limit to the flexural strength, σ_{bf}/σ_b , is 0.415. The value of σ_{bf} is small, but the value of its ratio is almost equal to that the industrial PMMA.

(4) In the experimental results on the canapé construction (KFRP/PMMA) with the organic fiber reinforced plastics (Kevlar-49 fiber/acrylic resin) laminated to the dental acrylic resin plate (PMMA), the flexural strength and the modulus of elasticity are 160 and 80% higher than those of PMMA, respectively. And the local failure which only KFRP shows disappears from the canapé construction. Therefore, it is recognized that the canapé construction makes the best use of the respective properties of both materials.

(5) The fatigue strength under pulsating plane bending considering the practical use is 130% more than that of PMMA, and the fracture mode at the KFRP part is a complete tensile fracture. Thus, this result clearly shows the excellent property of it as facing. The hybrid construction such as the dental plastics material not only gives a merit of the mechanical effect, but also found satisfactory for the dental use from the point of the manual molding technique. And this new composite material differs from the usual mixed-composite material, and these results obtained will contribute to the fundamental data on the reinforcing means of the dental plastics material in the practical use.

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