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Conceptual Design of the Three Unit Fixed Partial Denture with Glass Fiber Reinforced Hybrid Composites

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Glass fiber 강화 복합레진을 사용한 3본 고정성 국소의치의 개념 설계 연구

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나경희·이규복·조광헌

본 연구에서는 knitted glass fabric 강화 레진에 대한 치과보철소재로서의 적용가능성을 평가하기 위한 목적으로, 가장 높은 수준의 교합하중이 작용하게 되는 구치부 3본 고정성국소의치에 이 재료를 사용하는 경우에 대해 해석을 수행하였다. 우선 구치부3본 고정성국소의치에 대해 knitted glass fabric 강화 레진을 적용한 두 가지 설계 개념을 상정하였고, 각 설계형상에 대한 유한요소해석을 하였다. 강도 평가를 위해서75N의 생리적인 반복 수직 교합 하중 조건을 부여, 보철물에 유도되는 국소응력을 피로강도측면에서 고찰하였다. 각각의 설계에는 knitted glass fabric을 모재로 하고 보강재로 unidirectional 형의 glass 복합재가 사용되었다.

본 연구에서 개념설계 된 두 가지의 3본 고정성국소의치는 수직 교합 하중 75N 에 대해 충분한 강성과 강도를 가진 것으로 분석되었다. 가공치와 knitted caps사이의 연결 부위에서 국소적인 응력 집중이 관찰되었으나 그 크기는 재료의 피로강도 범위 이내였으며 국소적인 설계변경을 통하여 응력분포를 더욱 개선할 수 있을 것으로 추정하였다. 본 연구를 통해 knitted glass fabric 은 새로운 치과 보철 소재로서의 그 가능성이 기대된다.

key word : knitted glass fabric, unidirectional glass, fatigue resistance, three unit bridge restorations, finite element analysis

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I. INTRODUCTION

The fracture mechanics of dental restorations made of ceramics and/or filled acrylate resins, i.e. composite resins, is currently under investigation. As an attempt to increase the resistance to fracture, the latter materials have first been reinforced with metal strengtheners1). Fibre-reinforced composite formulations instead are now examined and intended to serve as structural components for various dental appliances such as prosthodontic frameworks, dentures and splints2). Studies on short2,3) and long continuous fibres4) have recently been reported. Carbon, polyethylene or glass fibres have been evaluated by several research groups. They are usually arranged in a unidirectional mode (no multidirectional organisation) to locally reinforce composite resin matrices in tooth restorations.

Although fibre reinforced polymers are now being considered as dental materials due mainly to their advantageous mechanical properties, some problems that can limit the clinical use of fibre-reinforced composite systems in dentistry have still been reported to occur, some of these are summarised as follows : 1) poor impregnation of the fibres5), 2) insufficient bonding to the resin matrix6-8), 3) mechanical weakness of the filled resin, 4) the excessive handling characteristics and 5) the small size of teeth to be restored or replaced.

Various continuous fibres have been tested. Carbon fibres have lead to unaesthetic black composites, with additional problems of polishing9); with polyethylene fibres, a good adhesion with the matrix is difficult to obtain10); glass fibres may be preferred because of their aesthetic qualities and ease of bonding to the matrix, providing the use of an appropriate silane coupling agent11). Two types of reinforcements, unidirectional (UD) and woven patterns, have been considered11). Unidirectional fibres can be useful in pontics of fixed partial dentures where reinforcement in one specific direction is needed; bi-directional weaves reinforce in two directions which can be useful in crowns where stress is not applied in a given direction. UD and woven reinforcements are currently used as strips but are not able to easily reproduce the shape of a tooth. Another type of fibre architecture, knitted fabrics, has been shown to be highly resistant to impact and fracture12), and to be easily drapable13). Indeed, due to the local stretching of loops, knits exhibit lower stiffness, can undergo larger deformations and behave more isotropically when compared to weaves. Knits will thus be impregnated to obtain a thin composite shell to reinforce dental prosthetic restorations. An additional veneering resin would be added to the reinforcement to improve resistance to wear and obtain the desired aesthetic aspect.

Use of knitted glass fabric (acrylic resin impregnated) in dentistry crowns restoration underneath the composite resin veneer will be justifiable only if it can resist the varied spectrum of occlusal loads and then increase the mechanical strength of the restoration. Having relatively lower stiffness, the knitted material is expected to improve the impact resistance of the veneer. It has been shown that this material can increase the toughness of the crown by prohibiting cracks from propagating. Due to its lower stiffness, however, it has been questioned whether this relatively soft material can sustain the occlusal loads. In this regard, a preliminary study was performed to investigate if the knitted glass fabric reinforced resin is mechanically strong enough to resist as high an occlusal load as when used in single crown restoration. Aside from the apparently promising resistance to compressive stresses in single crown restoration, however, some questions were raised particularly about the fatigue strength of the knitted materials when used in bridge restorations in which tensile stresses induced by bending need to be taken into careful account. Higher stresses in the tentative three unit bridge of knitted glass fabric reinforced composites were observed than their fatigue strength. A further structural design/analysis seems necessary to evaluate the load bearing capability of the knitted materials.

With the above in mind, two new concepts relative to three unit bridges for teeth in the posterior arch which are subject to the highest possible occlusal loads were proposed and analysed. Hybrid system of the knitted glass fabric and unidirectional glass tape was tested as reinforcement.

Detailed scope of the work is summarized as follows: 1) Development of initial design concepts for fiber reinforced composite bridge three unit bridge for posterior arch teeth, 2) Stress analyses for the three unit bridges consisting of the knitted materials - glass fabric impregnated with dentistry resin - for crown applications, and UD glass materials for bridge structure, 3) Main consideration was placed on the evaluation of the static resistance of the composite materials under physiological occlusal loading conditions.

Ⅱ. MATERIALS AND METHODS

1. Fibre architectures and material properties

Fibres exist in a wide choice of textile architectures (knits, weaves, braids or UD), with varying mechanical properties and shapability. Knits are in this case the most appropriate as they have been shown to have the highest drapability[13)], a characteristic necessary for draping over complex 3D tooth size shapes in order to obtain fibre-reinforced frameworks equivalent to the metal support of a crown. Two main types of knitted structures exist: warp and weft knitted fabrics which differ from their loop arrangement, as represented in Fig. 1. The former has been shown to be the most easily drapable[13,14)].

Various biocompatible, thermoset or thermoplastic matrices, including dental acrylics and polyamide 12 (PA12), are compared in ref 1 & 15. Since no apparent advantage was found in favor of thermoplastic materials over thermoset, however, the acrylic resin appears to be only option as the matrix material. As for the fibres, since the fibres need to be very stable in the intra-oral environment, low water absorption and

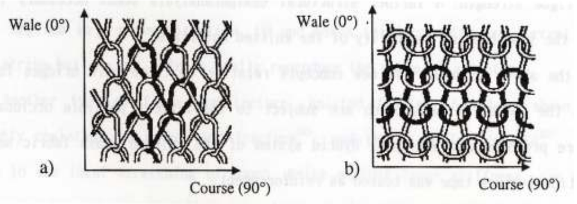

Fig. 1. Main types of knitted structures : a)warp ; b)weft

high mechanical properties are required: acrylates, UHMWPE and PEEK thus seem to be good candidates. Thermoplastics are not easy to use in dentistry, however, as they require high processing temperatures, which mean lack of flexibility in dental use. Glass fibres are potentially the most suitable candidates for dental restoration and in the present study as well. A glass fibre knit (#6181-08) from the firm Tec Knit was the only candidate material of which the material properties were available for the present study. 68 tex fibres are made from E-glass, with the sizing PPG 1383. This double warp knitted fabric has the following characteristics: 500 $g.m^{-2}$, with 28 wale/inch and 18 course/inch. Thus the fabric has a high loop density for a maximum covering of the shell surface while being a thin knit of continuous glass fibres. More detailed information including the process condition can be found in ref 15. The mechanical properties of glass fibre based composite are summarized in Table 1 together with some other dentistry materials. Unidirectional(UD) materials in Table 1 were used as reinforcement to the knitted fabric thus forming hybrid composites.

As is mentioned in the bottom of the table, stiffness and strength of the glass/acrylic laminate were estimated values based on elementary laminate theory. What is called a rule of mixture is used in the derivation of the stiffness data, that is,

(1) $E = Ef\ Em\ /\ \{(1-\ Vf) + Em\ Vf\ \}$
(2) $E// = Ef\ Vf + Em\ (1-\ Vf)$

where, E// ,E are stiffnesss of the UD materials parallel to fibres and transverse to the fibre direction, respectively. Ef and Em are moduli of fibre and matrix, and Vf the volume fraction of fibres in the UD material.

The stiffness and strength of the quasi-isotropic laminate with the stacking sequence of (0/± 45/90), were calculated using the 10% rule which assumes that angled layers in the laminate contribute only 10% of the layers with fibres parallel to the laminate axis system.

Table 1. Comparison of elastic properties of dentistry materials

Material	E(GPa)	v	Strength(MPa)
Knitted fabric reiforced composite[14)	5	0.30	13.0 Tensile fatigue[14)
Filled acrylic resin(composite resin)	10	0.25	
UD continuous tape (// t fibres)	43	0.3	1000-1200
UD continuous tape (⊥ to fibres)	6	0.3	100
Quasi- isotropic laminate (0/±45/90)	(*) 15.25	0.3	(*) 400(Static) (*) 100(tensile fatigue)
Dentin	15	0.30	
Ceramic	70	0.20	
Amagam	34	0.35	
Gold alloys	86	0.30	

(*) Stiffness and strength of the glass/acrylic laminate were estimated values based on elementary theory.

2. Preliminary design of three unit bridges with hybrid composites

A three unit bridge aiming at posterior teeth restoration was conceptually designed and analysed in the preliminary study to investigate the potential of the above mentioned knitted glass materials. The overall structure was assumed to be constructed using the knitted glass fabric impregnated with dental acrylic material. The result of static stress analysis shown in the Fig. 2, however, has revealed that the fatigue strength of that bridge of knitted material was not high enough to resist the vertical occlusal load of 75N acting at the pontic in the bridge. Fig. 2 shows the distribution of the maximum tensile stresses in the preliminarily designed three unit bridge of knitted glass materials. Some detailed dimensions of the bridge geometry can be found in the following figures, i.e. Fig.s 3 and 4, which show other concepts of the bridge design developed during the present study.

The bridge should sustain not only static ultimate load but also those repeated loads over its designed life. The level of maximum tensile stresses in the knitted materials, compared with its fatigue strength 13MPa, are observed higher by 2MPa. Improvement in the strength of the bridge structure looks a must. Since the thickness of the knitted material was already as thick as 1 mm it would not be an option to increase the thickness to lower the level of the tensile stresses. A single possible option will be to use stronger materials without increasing thickness.

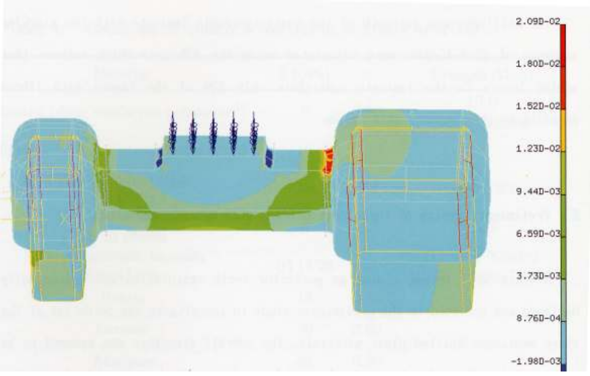

Fig. 2. Stress analysis results (maximum tensile stress : approx. 15MPa.) for the three unit bridge conceptually designed in the preliminary study.

Due to the bridge geometry, i.e. short span with thick cross section, shear stress plays as important a role as bending. A diagonal tension field is observed in the stress distribution across the span of the bridge.What seems to need mentioning here, however,

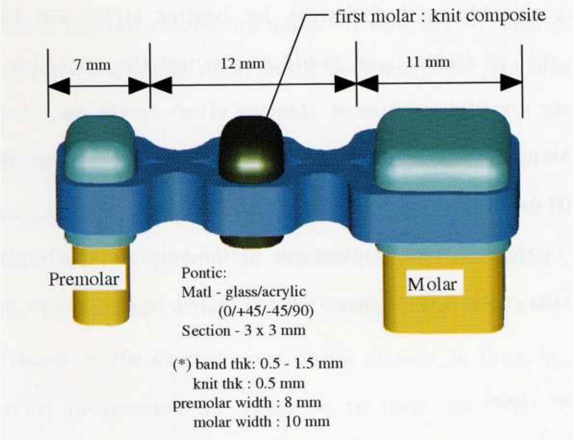

Fig. 3. CAD model of the 3 unit bridge of the knitted materials with quasi-isotropic laminate band. The pontic of the missing molar is assumed to be made of knitted materials. Other materials such as composite resins can also be used for the pontic.

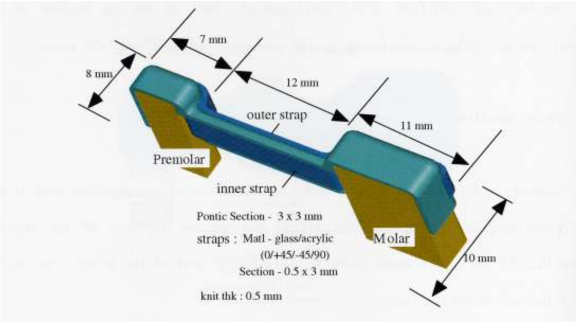

Fig. 4. Half of the bridge (shape of each part is shown with the analysis result). Heights of the abutment 6 mm.

is that the above estimate is for a bridge of posterior teeth. The knitted material might be made strong enough for a bridge of anterior teeth, where both the load and span are small, whereas the space for the height of the bridge would be bigger. In the present study, main aim was to develop the three unit bridges in order to investigate the possibility of using hybrid type composites to meet the fatigue strength for the posterior bridges subject to the highest spectrum of occlusal loads. In the hybrid type composites, the unidirectional tape of glass fibres could be introduced side by side with the knitted materials.

For reinforcement, unidirectional glass/acrylic material appears to be the material of choice. Stacking of the UD material with the sequence of (0/+45/-45/90) appears suitable, with 0 degrees for bending stress and 45 degrees for shear stress. And 90 degree layer should wrap around the pontic bar at the outer surface, thereby giving a gripping or stapling effect to the bar, thus keeping the bar from splitting. Resisting the secondary stresses especially at the junctional area by this 90 degree layer will be important for longevity.

According to the strustural arrangement of the reinforcing materials described above, two design concepts were suggested and tested in the present study.

1) Bridge of band

Geometry : As a simple way to manually construct the pontic connecting two abutments, a band of unidirectional glass/acrylic material was the first design concept to be tested, the geometry of which is shown below in the Fig. 3. Some important dimensions of the bridge, as well as of the constitutive materials, are also shown in the Fig.. The abutments of which the height are 6 mm were assumed to be covered with caps of knitted materials. To make sure that the entire restoration was made within 1.5 mm, it was assumed that the knit cap could be made with a thickness of 0.5 mm. With the current 1mm thickness, there will be no room for additional reinforcement.

The stacking sequence of the band is (0/+45/-45/90), of which the outer 90 degree layer is wrapping (or winding) the inner layers of (0/+45/-45). For the sake of convenience in the analysis, however, the band was regarded as a simple laminate, neglecting the 90 degree layer at the upper and lower surfaces of the pontic. The quasi-isotropic nature of this stacking made a further simplification of the modelling process possible by assuming the laminate was isotropic.

The pontic of the missing molar is assumed to be made of knitted materials. Other materials such as composite resins can also be used for the pontic.

In order to take into account the effect of the limited drapablity of unidirectional material, deliberate gaps were placed at the junctional area between the band and the abutments. Although in the present modelling, no filling material for the gaps was modelled, the size, shape of these gaps, and the effect of the filling material will need further elaboration, however, to achieve higher strength at those areas. Again, no veneer material was included in the analysis, which can be as thick as 1 mm at the occlusal surface, and 0.5 mm at other surfaces

The pontic molar was modelled from a mass of the knit composite. It can be taken out of the model, however, as it does not play an important role in the load carrying and load bearing function.

As for load condition, a vertical load of 75N at the top surface of the pontic molar, which is equivalent to the repeated occlusal load, was given.

2) Bridge with reinforcement straps

Geometry : This design concept is to reinforce the knit composites with straps of glass/acrylic laminate on the inside and outside surfaces of the knitted material. In the figure shown below is a section of half of the bridge, cut at the longitudinal symmetry plane.

As in the case of the band design, knit materials were assumed to have a thickness of 0.5 mm. The stacking sequence of the inner and outer straps was (0/+45/-45/90) as before. For the sake of convenience in the analysis, the strap materials were assumed here

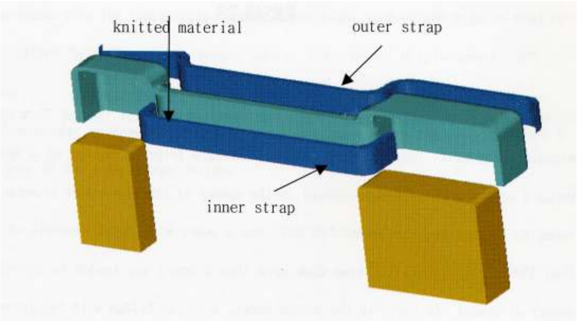

Fig. 5. Exploded view of the bridge shown in Fig. 4.

again to be isotropic.

An advantage of this concept is that a bridge can be manufactured with a single step forming process without excessive manual labour. Placing the laid-up straps on the upper and lower surface of the knit materials, forming this hybrid preform on the mould, and final trimming would provide a brief manufacturing sequence.

A distributed vertical (occlusal) load of 75N was given at the midpoint of the bridge on the span of 6 mm.

Both the above designs were made using the IDEAS 8 master modeller software program. Finite element meshes were made with 10 node tetrahedron (3D solid) elements. All the materials were assumed to be linear elastic.

Ⅲ. RESULTS

Stress analyses were carried out for the vertical occlusal load of 75 N on the midpoint of pontic, using IDEAS version 8 software program running on a Hewlett Packard work station. Careful control in the number of the degrees of freedom were found to be extremely important. As this was a model with total elements of more than 15000, the computation time took more than 2 hours and tended to exceed the memory allotment. In fact, in the second model, i.e. the bridge with reinforcement straps, a half model was used to reduce the degrees of freedom. This problem might have been avoided if the meshes were generated on a controlled manual manner. Due to the complex 3 dimensional shape of the model, however, it was necessary to use the automated mesh generator built in the IDEAS program.

Fig.s 6 to 9 are results for the band bridge. The overall displacement, principal strain I (the maximum tensile strain), and principal stress I (the maximum tensile stress) are plotted for the whole model as well as for the reinforcement band. It should be noted, however, that all the numbers in the contour bars shown in the right hand of the figure need to be multiplied by 1000 to get proper units, i.e. mm in displacements, MPa in stresses.

Fig.s 10 to 15 are the results for the bridge with reinforcement straps. As before, overall displacement, principal strain I (the maximum tensile strain), and

Fig. 6. Displacement in the bridge of band. Max. vertical displacement of approx. 0.045 mm

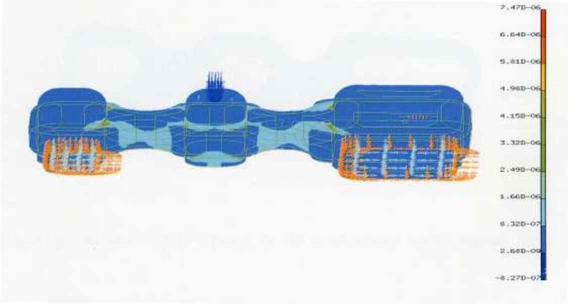

Fig. 7. Maximum tensile strain in the bridge of band. Maximum of approximately 0.45%

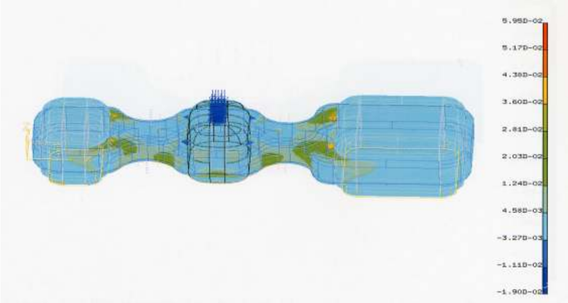

Fig. 8. Maximum tensile stresses in the bridge of band.

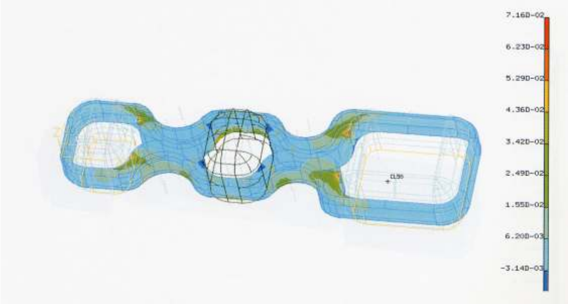

Fig. 9. Maximum tensile stresses in the reinforcement band: approx. 70MPa

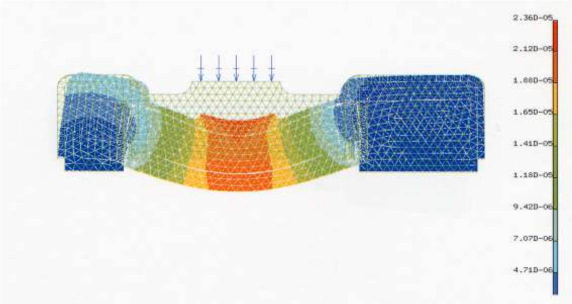

Fig. 10. Displacement in the band of reinforcement straps. Maximum vertical displacement of approximately 0.025 mm.

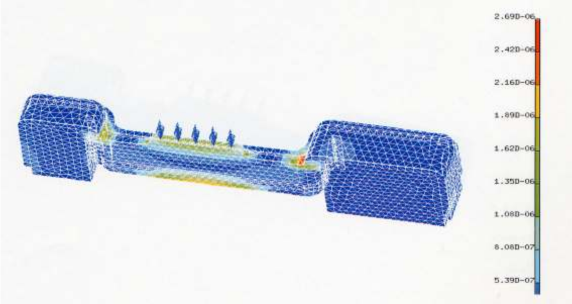

Fig. 11. Maximum principal tensile strain in the band of reinforcement straps. Maximum of approximately 0.26%

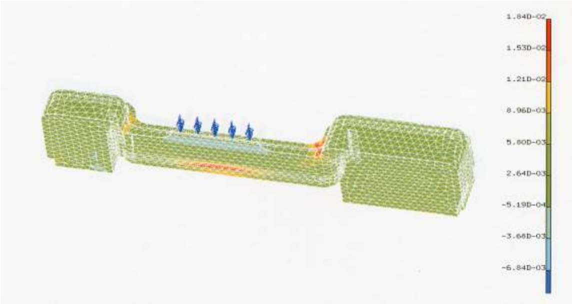

Fig. 12. Maximum principal tensile stresses in the band of reinforcement straps. Maximum of approximately 19MPa.

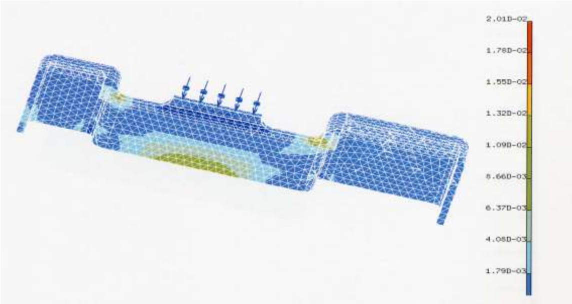

Fig. 13. Maximum principal tensile stresses in the knitted material of the band of reinforcement straps. Maximum of approximately 14MPa.

principal stress I (the maximum tensile stress) are plotted either for the whole model as well as for the reinforcement components. Again, it should be noted that all the numbers in the contour bars shown in the right hand of the figures need to be multiplied by 1000 to get proper units, i.e. mm in displacements, MPa in stresses.

3 dimensional meshes for finite element analysis can be observed in Fig. 6 and Fig. 10 for both bridge designs.

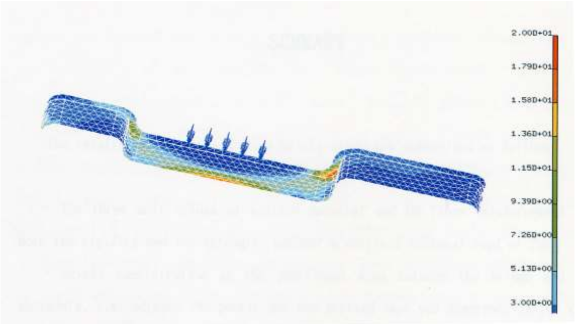

Fig. 14. Maximum principal tensile stresses in the outer strap of the band of reinforcement straps. Maximum of approximately 20MPa.

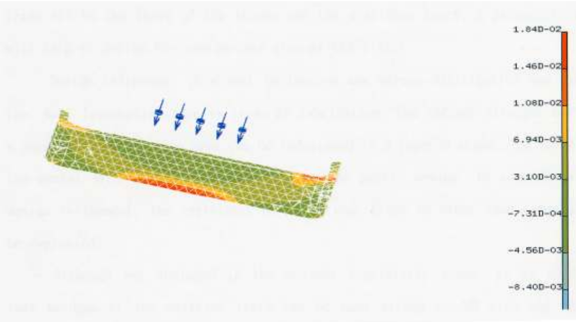

Fig. 15. Maximum principal tensile stresses in the inner strap of the band of reinforcement straps. Maximum of approximately 19MPa.

Ⅳ DISCUSSION

Basically two new design concepts have been suggested for the constructions of three unit bridge frame with FRP (fibre reinforced plastics). Stress analyses have been carried out to study their resistance against the vertical load of 75N acting at the midpoint of the bridge. Veneer materials were not included in the finite element modelling of bridges so that all the occlusal loads might be taken up by the fibre composite bridge. The maximum principal stresses - that is the maximum tensile stresses - were compared with the material fatigue strength to evaluate the resistance to repeated occlusal loads.

It is shown that vertical displacement at the first molar is 0.045 mm in Fig. 6. Though slightly higher than with the second model, it is small enough that it is still in the acceptable range.

Since the occlusal load of 75N was applied to the top surface (3 mm span) of the pontic molar, it was relatively concentrated on the midpoint of the span rather than in the case where the applied load was distributed onto 6 mm span in the preliminary study. Higher stress would be a natural result. The overall stress level, however, is still well within the material strength shown in Table 1.

Here, localized stress concentration is observed at the junctional areas between the pontic and both the premolar and molar. On the other hand, the level of the stresses are rather insignificant in other parts of the band. Stress concentration is more severe than in the reference case shown in Fig. 2. This is due mainly to the shape of structure that forms almost butt joint like connections - without filleting or rounding - and to the fact that contact areas at the joining area got smaller. Because of the complexity of the shape it was not possible to realise a smooth transition of the surfaces with IDEAS Modeller. However, since stress concentrations can be managed by careful surface redesigning, this design concept should not be underestimated because of the apparent higher stresses. In fact, even the stress of 70MPa, as a result of the stress concentration, is still within the safe envelope in terms of material fatigue strength. Filling the gap with knit materials or composite resin will also help lower the stress. A further refinement in the modelling together with a manufacturability study is therefore highly recommended.

Though a further study will be needed for a better design in accordance with a manufacturability study, in terms of rigidity, stress, and of producibility, this design looks promising and worth a further precise evaluation.

In Fig.s 10 to 15 are shown the results for the bridge with reinforcement straps. Due to the relatively simple shape in terms of modelling it was possible to introduce fillets of 0.5 mm radius at the junctional areas between the pontic and the abutments. The result was a significant improvement in stress concentration. This indicates that further reduction in the stress would be possible by more elaborate surface designing.

The highest stress throughout the whole bridge is about 20MPa well below the fatigue strength of 100MPa, and 14MPa at the knit material which is slightly higher than the material strength of 13MPa. Stress at the bottom surface of the mid part of the bridge is higher than other areas, but it is thought to be reduced by putting additional reinforcement there. Since stresses at the lower surface of the bridge at the junctional area are by far within the material strength, it seems reasonable to cut out bridge materials and slim-line the structure here. It is a promising indication since providing a suitable relevant amount of space here is important for the health of inter-dental papilla tissue.

The overall displacement results for this design also make it look to be the most promising compared with the other designs.

Ⅴ. SUMMARY

The results of the present feasibility study are summarized as follows,

1. The three unit bridge of knitted material and UD fibre reinforcement has both the rigidity and the strength against a vertical occlusal load of 75N.
2. Stress concentration at the junctional area between the bridge and the abutments, i.e. between the pontic and the knitted caps was observed. In the case of the bridge with reinforcement straps, it was partly shown that the concentration problem could be improved by simply increasing the fillet size at the area. Further refining in the surface of the junctional area will be needed to ensure a further improvement in the stress distribution. This will require some trade off in the level of the stress and the available space. A parametric study will help to decide the appropriate size of the fillet.
3. Design refinement is a must to improve the stress distribution and realize the most favourable shape in terms of fabrication. The current straight bar with a constant cross section area can be redesigned to a tapered shape. The curve from the dental arch should also be placed on the pontic design. In accordance with design refinement, the resistance of the bridge frame to other load cases should be evaluated.
4. Although not included in the present feasibility study, it is estimated that bridges of the anterior teeth can be made strong enough with the knitted material without further reinforcement using unidirectional materials. In this regard, a feasibility study on design concepts and stress analysis for 3, 4, 5 unit bridge is suggested.
5. Two types of bridge were analysed in terms of fatigue. The safe life design concept, i.e. fatigue design concept, looks reasonable for the bridge where if cracks should form and propagate there is virtually nothing a dentist to do. The bridge must be designed so that no crack will be initiated during the life span. In the case of crowns, however, if constructed with composite resin with knitted materials, it might be possible to repair them, which in general is impossible for crowns of PFM or of metal. Therefore for composite resin crowns, a damage tolerance design concept can be applied and reasonably higher operational stresses can be allowed. In this case, of course, a periodic inspection program should be established in parallel.
6. Parts of future works in terms of structural viewpoint which need to be addressed are summarized as the following: 1) To develop processing technology to accommodate design concepts; 2) More realistic modelling of the bridge and analysis-geometry and loading condition. Thickness variation in the knitted material, taper in the pontic, design for anterior tooth bridge, the effect of combined loads, etc, will need to be

included; 3) To develop appropriate design concepts and design goals for the fibre composite FPD aiming at taking the best advantage of knitted materials, including the damage tolerance design concept; 4) To develop testing method and perform test such as static ultimate load test, fatigue test, repair test, etc, as necessary.

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