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Fibre reinforced composite dental bridge. Part I: experimental investigation

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Abstract

This experimental investigation aims at revealing the mechanical behaviour and failure pattern of direct fibre-reinforced resin-bonded dental bridge with various designs. To evaluate the overall effects of some newly developed dental materials, in the experiment, genuine composite dental bridge specimens are prepared and tested. The ultimate load, stiffness and mode at the failure of the bridges are measured and compared with the design variations. A good agreement between test and some clinical observations is demonstrated. It is verified that the weakest region appears across the pontic–abutment interface in the composite bridges. This study suggests that the composite bridges reinforced by fibres and supported by adjacent teeth could be of a higher structural strength and stiffness; therefore would provide better clinical performances.

Keywords: Dental restorative materials; Composites; Dental adhesive; Failure analysis; Mechanical test

1. Introduction

In restoration dentistry, a relatively new technique of etching an enamel surface with acid and bonding composite artificial teeth directly to the adjacent natural teeth reinforced with high-density fibres without metal frameworks has produced good outcomes [1–4]. With the construction of more and more direct resin-bonded bridges, its advantages of minimal tooth preparation, little or no tissue removal and low laboratory costs have attracted extensive attention [5–7]. Definitely, such a new technique needs a thorough evaluation as it alters traditional and well-proven clinical concepts so radically. It is known that the debonding in the interface between the abutment and pontic represents a major mode of failure, though the initiation, progression and pattern of debonding remain unclear [8,9]. The rapid development and relatively short clinical history of the current composite resin-bonded bridge technique have given rise to concerns about the inadequate evaluation of the procedure.

Recently, there has been a growing interest in the experimental investigation of dental prostheses. To identify in vitro, whether the adhesive fixed posterior inlay dentures (AFPID) fabricated with a fibreglass-reinforced system have adequate fracture strength and a satisfactory marginal adaptation which could occur under clinical conditions, Behr and co-researchers [10] presented the experimental investigations of static and fatigue strength on three-unit posterior inlay bridge models in 1999. This work attempted to simulate an artificial oral environment and was equivalent to 5 years of wear, thermocycling and mechanical loading.

With regard to the direct fibre-reinforced dental bridge, the effect of span-to-thickness (L/D) ratio on flexural properties of fibre-reinforced composite (FRC) used for dental restorations was studied by Karmaker and Prasad [11] for both the conditions of constant thickness and constant support span. Based on their experimental investigation, the absolute load bearing capabilities were higher than the ones expected, although the calculated flexural strengths and moduli

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are lower at shorter support span. Such an interesting finding suggests that the presence of fibres within the bridge could be capable of supporting considerably higher loading than the composite material properties allow.

A growing body of research on the bond strength of the adhesive has also been reported [12–14]. Unfortunately, these studies were carried out only at material model levels rather than a whole bridge system. From the literature, there have been no experimental reports regarding the direct fibre dental bridge despite its great practical significance.

This piece of work is expected to provide an experimental investigation into the direct fibre-reinforced composite dental bridge to understand its quasi-static mechanical behaviour, which aims at: (1) measuring the deformations of the bridge structure; (2) determining the failure load, failure deflection and failure location; (3) identifying the role of the fibres; and (4) exploring the effects of adjacent teeth. Also, the experimental results are compared with the clinical observations.

2. Materials and methods

In this study, the specimen is based on a two-unit anterior cantilever bridge model that includes a maxillary right incisor as an abutment and a maxillary left incisor as a pontic bonded by composite resin and reinforced fibre as shown in Fig. 1. The pontic is made of composite resins which is set through polymerization and comprise a blend of hard, inorganic particles bound together by a soft, polymerizable resin matrix. To reinforce the strength of the composite resin and improve the performance of the resin-bonded bridges, a high modulus, plasma-etched polyalkane fibrespan (Nulite System International) was embedded into the pontic and bonded to the abutment.

To observe the effects of design variations, six cases of the two-unit cantilever bridge are considered in the experiment, which are constructed in non-fibre, single-fibre and double-fibre, with and without adjacent teeth, respectively as in Table 1. Primarily, these different designs aim at quantifying the effects of the fibre reinforcement and support from the adjacent teeth. It is desirable that the tests would lead to a preliminary understanding of the bridge characteristics, e.g. ultimate load, deflection at failure, failure mode and failure location.

To explore the mechanical response of the dental bridges under different load positions, four loading sites are set on the occlusal edge of each bridge specimen along the line of actual loading, as illustrated in Fig. 1. It

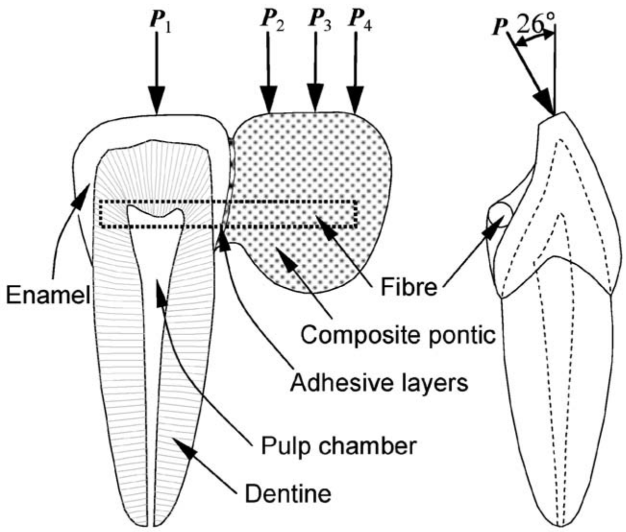
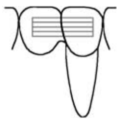
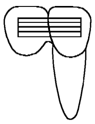
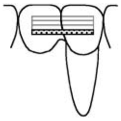
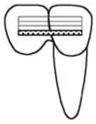
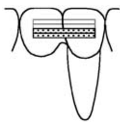
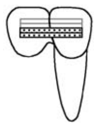


Fig. 1. Schematic of the dental bridge model.

Table 1
Load (N) and deflection (mm) at failure

Designs	With adjacent teeth			Without adjacent teeth		
	Diagram	Load	Deflection	Diagram	Load	Deflection
Non fibre		173.8	0.160		92.8	0.105
Single fibre		196.1	0.245		174.2	0.165
Double fibre		221.9	0.264		211.5	0.229

is assumed that the bite force was 26° to the vertical axis that represents the angle at the first contact of teeth during biting [15,16].

The number of tests undertaken depends primarily on the availability of the specimens and associated preparation/test time. According to the basic test objective, to enable a preliminary estimation of the structural behaviour, the procedure allows two specimens to be statically tested for each design. Thus twelve specimens are prepared in total.

Considering the primary goal of this study, man-made abutment teeth are adopted for bridge specimens to limit the uncertainties caused by the uncontrollable quality of human incisors. These abutment teeth are made by cementing a cast brass core and a porcelain jacket crown together as illustrated in Fig. 2. The cast brass core and porcelain crown are made separately in accordance with the average dimensions of the tooth structures [17] and following the normal procedure for crown preparation. The bonding surfaces on each pair of root and crown are carefully shaped and sanded to ensure a best possible fit.

The cast brass is employed to make the root and dentin of the abutment due to its low cost and excellent manufacturability. The choice of porcelain crown is based on the similarities of its material properties with those of the enamel ($E = 68.9\,\text{GPa}$, $v = 0.28$ for the porcelain and $E = 60.0\,\text{GPa}$, $v = 0.33$ for the enamel, respectively [18,19]). Also, good retentive strength, as reported on anterior-etched porcelain bridges attached with composite resin [20] and wide clinical application makes porcelain the most suitable material for manufacturing the crown of the abutment tooth. After assembling, the abutment tooth is then set in an impression of the anterior, into which a special model resin (DVA Polyroqq die and model resin) is carefully syringed to fabricate a cast to support the abutment tooth together with the adjacent teeth.

The abutment teeth are cleaned with water in an ultrasonic cleaner. The bonding areas on the porcelain crown are air-abraded and etched for 1 min using 37% orthophosphoric acid gel (Etchalite, Nulite System International). This is followed by a thorough rinsing with water, drying with air blasts, coating with enamel bond (NS Bond Universal Adhesive, Nulite System International), and light curing with an Optilex 400 unit (Demetron Research Corporation) for 15 s. Before the pontic is bonded to the abutment, a thin layer of the hybrid resin composite Nulite F (Nulite System International) is built up over the bonding areas on the abutment and the pontic, respectively.

Each resin pontic is fabricated from Nulite V (Nulite System International), a visible light-activated resin-based hybrid composite, light cured for 2 min, contoured, and polished according to the construction procedure [6].

All the prepared parts (as shown in Fig. 3) are randomly divided into six groups of two for each design by carefully bonding the pontic with non-fibre, single-fibre or double-fibre reinforcement, respectively. The areas under the pontic are relieved so that no contact of the pontic and the DVA model resin base would result during loading. Also to maintain a correct proximal relationship, the bridge is arranged to be physically separated from the adjacent teeth by a very small gap (≈0.1 mm).

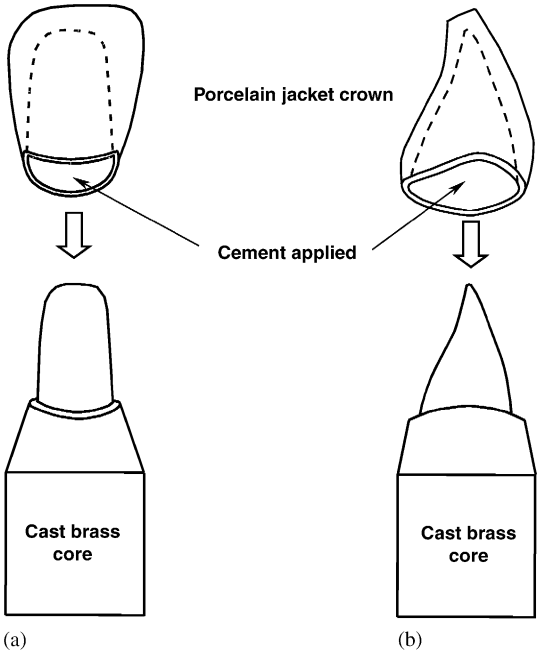


Fig. 2. Abutment tooth manufacturing: (a) Lingual view and (b) Proximal view.

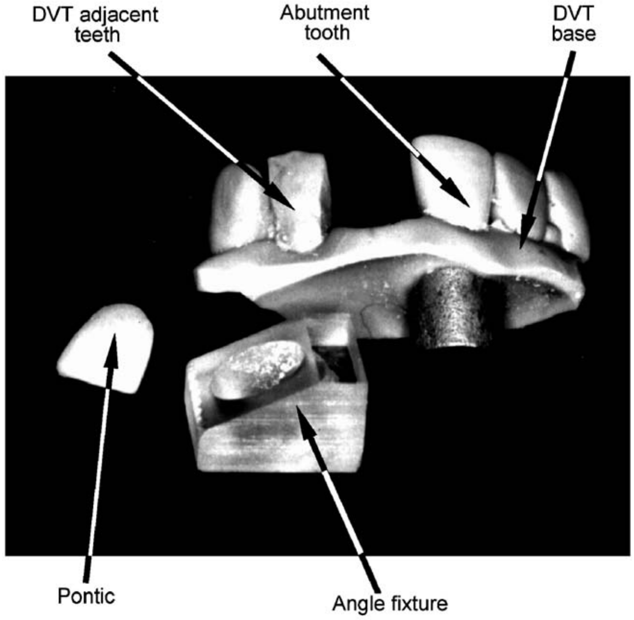


Fig. 3. Resin pontic, abutment and adjacent teeth cast, and plastic angle fixture.

To simulate the contact angle during biting, a special angle fixture made of perspex plastic is bonded to the brass root of an abutment. The finished bridge models are then positioned in the middle of a plastic mould ring placed on a glass slide and bedded into a mixed paste of tray resin which then sets. The paste of tray resin is made by mixing Trayresin powder (Dentsply/York Division) with an acrylic resin (Vertex). The resulting cured resin has a modulus of elasticity approximating to that of natural cortical bone ($E = 13.7$ GPa). The bottom of the specimen is wet polished by sand paper to secure a flat contact between the specimen and the platform of the testing machine.

The experimental set-up is illustrated in Fig. 4. The static tests are performed using a computer-controlled precision universal testing machine (Autograph AG, Shimadzu Corp., Tokyo, Japan) with displacement measurement system. The automatic data acquisition system stores all test data and provides a database for carrying out statistical calculations on a PC.

The bridge specimen is appropriately adjusted on a rigid metal platform of the testing machine so that the loading element could make contact with the desired loading position as accurately as possible. Fig. 4(a) and (b) show the dental bridge model and the loading element in both facial and proximal views. A concentrated load is applied by the loading element at different load positions of each specimen. The crosshead speed is set at $0.05\,\mathrm{mm/s^{-1}}$ to eliminate any impact.

The static tests are performed at room temperature (26°C). Each specimen is subjected to a series of loading–unloading cycles at the specified load position. With no prior knowledge about failure loads, values of 20, 50, 100 and 150 N are chosen as the loading level for each cycle. If failure does not occur by 150 N, the load level is then increased by 50 N until the specimen failed.

3. Results and discussions

3.1. Failure mode

It is observed that the failure in most specimens with fibre reinforcement results from a stable fracture along the interface between the abutment and the pontic (the porcelain-composite resin bond) as shown in Fig. 5(a) with adjacent teeth and (b) without adjacent teeth. The presence of the fibres bridging the crack leads to this stable crack extension.

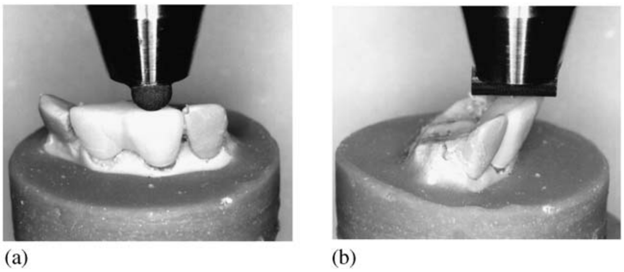


Fig. 4. Experimental set-up showing facial and proximal views of pontic with adjacent teeth: (a) Facial view and (b) Proximal view.

For the specimens without the fibre reinforcement, the failure is catastrophic resulting in complete dislodgement of the pontic in both designs without and with the adjacent teeth as shown in Fig. 5(c). This failure mode suggests that the fibre reinforcement plays an important role in supporting and retaining the bridge even after the bridge debonded, thus fulfilling a fail-safe situation from a cosmetic point of view.

In a clinical study of direct composite bridges, Culy and Tyas [8] have found that the failure usually took place at the enamel–resin interface for the cohesive resin composite. It was also reported that the resin-bonded bridges most frequently fail cohesively at the resin–metal interface [21,22]. Thus, the failure location in this study appears consistent with these clinical observations.

In the present investigation it is noticed that the failures occurred adhesively as shown in Fig. 5(c), which

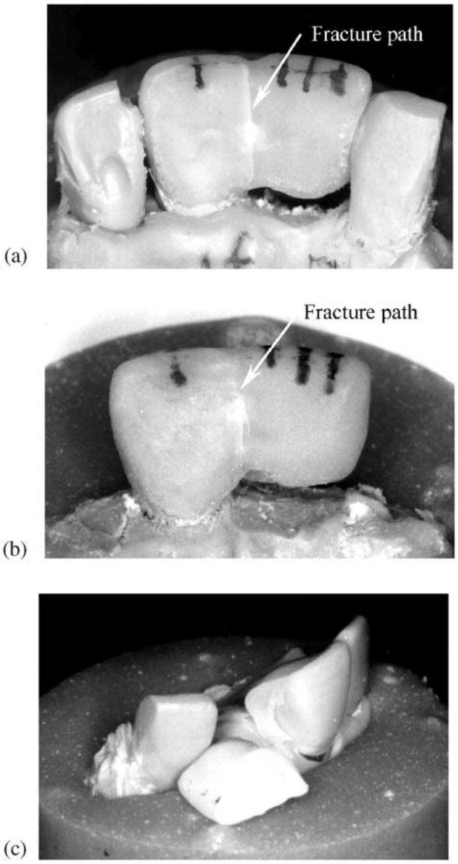
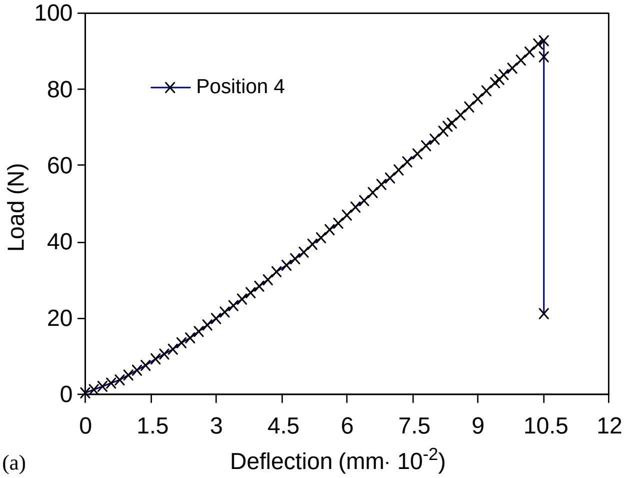


Fig. 5. Failure modes: (a) Fractures at the specimen with fibre reinforcement and adjacent teeth; (b) fractures at the specimen without adjacent teeth and (c) cracking at the specimen without fibre reinforcement and with adjacent teeth.

implies that the shear bond strength or interfacial toughness between porcelain and composite resin seems to be weaker than the one between enamel and composite resin. This supports the findings reported by Fritz and co-researchers [23] in 1996 that an adhesive composite-etched enamel bond could be extremely strong. In an experimental study on the failure of resin-modified ionomers under shear loading, Sidhu et al. also identified that failure occurred cohesively, adhesively or together with different materials [24]. Both these studies indicate that failures of bridges differ from the material tested.

3.2. Load and deflection at failure

Fig. 6(a) shows the typical plots of load–deflection curves at failure for the non-fibre design without adjacent teeth. Fig. 6(b) depicts the same for the double-fibre designs with adjacent teeth. It is found that in all the static tests of the bridge structures, there is almost no noticeable yielding or plastic deformation prior to failure. This implies a macro brittle failure mode. In this research no attempt is made to use fracture mechanics to analyse the fracture behaviour since this would have required considerably more experimental information to determine the fracture mechanical properties of the materials involved.



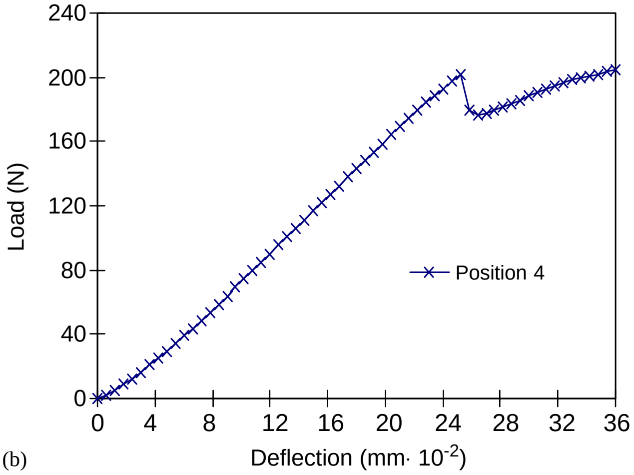


Fig. 6. Typical plots of load–deflection curves at failure: (a) non-fibre without adjacent teeth and (b) double-fibre with adjacent teeth.

It is also observed that, in the test of the non-fibre design, the loads suddenly drop at the failure point, regardless of the presence of the adjacent teeth. This reveals that the failure of the non-fibre design occurs in a typical brittle manner. However, the failure processes for the single and double-fibre designs appear more complex owing to the contribution of the fibres. In the cases of design with fibre, an initial failure occurs in the bonding interface between the pontic and abutment. Nevertheless, the bridge may not fail immediately, as the reinforcing fibres continue to play a role in supporting the bridge. As a consequence, the deflection continues to increase whereas the load reduces. Such a phenomenon is more apparent in the case of the double-fibre design with the adjacent teeth as shown in Fig. 6(b), where the final failure load even reaches the same level as the initial one after considerably more displacement appears. The fibres indeed provide the bridge with a stable ''post-failure'' supporter such that the bridge may persistently survive under a reduced load level for a substantial period.

The range of the loads to failure in the experiments of bridge specimens are summarized in Table 1. It is quantified that the highest mean failure load occurs in the case of the double-fibre design with the adjacent teeth. For the specimens with adjacent teeth, it is interesting to note that as the fibre number increases, the failure load increases by about 13–14%. While for the specimens without adjacent teeth, the failure load in single-fibre design is almost 50% higher than that of non-fibre design and that of double-fibre design is 20% higher than that of single-fibre design. This confirms the substantial role of the fibres in improving the bridge's overall strength.

Moreover, from Table 1, it is also found that the specimens with the adjacent teeth have a higher loading level at failure compared with that of the corresponding specimens without adjacent teeth. Such a phenomenon appears more significant in the single or the non-fibre design cases. Taking the non-fibre design as an example, the failure load of the specimens with the adjacent teeth is significantly higher than that of the ones without the adjacent teeth (by 46%). This suggests that the adjacent teeth can share a substantial amount of load and could play a more significant role in the non-fibre design.

In addition to the failure loads, the corresponding deflections at and after failure are also of major concern for dental bridges. Table 1 presents the mean values of the ultimate deflections at failure in the static tests. It is clear that the designs with the adjacent teeth have a much larger ultimate deflection than those without the adjacent teeth. Also, the design of the double fibres can significantly increase the ultimate deflection, especially for those without the adjacent teeth. From this point, the double-fibre design with the adjacent teeth has the highest overall stiffness at failure.

It is useful to be aware that physical experiments are often subject to diverse errors, uncertainties and statistical scatter. The inconsistency is found in the failure loads and deflections due to the limitation of each test group that has only two specimens. Taking the loads at failure as an example, it was found that the errors between the measured values and the mean value for each design group vary from 8% (single-fibre design without adjacent teeth), 9% (double-fibre design with adjacent teeth), 14% (double-fibre design without adjacent teeth) to 27% (single-fibre design with adjacent teeth). However, it is also found that the slopes of the load–deflection curves are the same for the same design group. Better results could be achieved by a statistical analysis with more specimens, for e.g. the eight specimens in each design as suggested by Rosentritt and co-workers [25]. To conduct a more detailed and a more reliable experimental investigation, a larger number of specimens and a more thorough test procedure would be required, but it is beyond the scope of this work.

4. Concluding remarks

In the study, the failure modes and failure locations of the direct fibre-reinforced composite dental bridge structures with and without adjacent teeth are experimentally investigated in detail. The experimental results show a good agreement with the clinical observations. It is found that the bonded interface is indeed the weakest region in the composite bridges. Also, it is suggested that the composite resin reinforced with high modulus polymer fibres and the presence of adjacent teeth could significantly increase the structural strength and stiffness of the bridge and therefore improve its clinical performance.

The experiments reported here are intended to be preliminary in nature and are not a definitive clinical study. It provides some original observations in the structural responses of the bridge. Moreover, it can be considered as a pilot study for further experiments such as thermal and/or fatigue tests for the direct composite dental bridges. However, due to the limitations of the experiment, no detailed investigation is performed to analyse the failure mechanism of the bridge. For understanding better the fracture behaviour of the structure, finite element simulations of the experiments will be used to evaluate the detailed stress and displacement distributions in the structure, especially on the interfaces, which are presented in the companion paper [26].

Acknowledgements

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