Influence of denture tooth thickness on fracture mode of thin acrylic resin bases: An experimental and finite element analysis

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The fracture resistance of acrylic resin denture base is one of the factors controlling the safety and longevity of removable prostheses, as well as patient satisfaction. Previous reports have shown that acrylic resin fractures occur in 57% to 64% of all removable dental prosthesis failures[1,2]; these fractures typically initiate at sites susceptible to masticatory stress.[3-5] According to previous studies, the site of stress concentration in the denture base may depend on the position of the denture teeth and retainer, denture movement, and the occlusal scheme.[6-10] The stress is often concentrated by the reduced interarch distance at the posterior edentulous ridge area that results from the wear of the remaining natural teeth and/or the extrusion of opposing teeth.[11,12] The opposing dentition may be in close proximity to the alveolar ridges of the edentulous area. The mechanical requirements of a denture base that is to be subjected to high stress under masticatory function must be optimized.[13-15] The presence of a denture tooth has been

ABSTRACT

Statement of problem. The optimum selection of denture teeth for patients with a reduced interarch distance has not been established.

Purpose. The purpose of this in vitro study was to investigate the influence of denture tooth material and thickness on the fracture resistance of thin acrylic resin denture bases.

Material and methods. Acrylic resin (AC), composite resin (CO), or ceramic (CE) molar denture teeth were embedded in denture base blocks (2.0 mm thick). The distance from the central fossa to the tooth base was 0.5, 1.0, 2.0, or 2.5 mm for AC and CO, and 1.0 mm for CE (n=7), with a total thickness of 2.5 mm for all specimens. Each specimen was placed on a 3-point flexural setup with a shorter (8 mm) or longer (12 mm) support span than the tooth width and vertically loaded. A finite element analysis was performed to assess the stress distributions. The effects of tooth thickness and support span were statistically tested with ANOVA, followed by the Tukey honestly significant difference post hoc test (α= .05).

Results. With the shorter support, the mean fracture load was higher in CO than AC, regardless of the tooth thickness. Under the longer support, the mean fracture load with the CO decreased significantly as the tooth thickness increased, with increased maximum stress. Some CO tooth specimens of 2.0 mm or 2.5 mm thickness failed at the tooth-denture base interface at significantly lower loads than those exhibited by tooth fractures. CE showed minor cracks before bulk fracture.

Conclusions. Higher fracture resistance was indicated with CO; however, the resistance decreased as the thickness of the CO tooth increased. (J Prosthet Dent 2015;114:122-129)

reported to decrease the strength of the acrylic resin denture base substantially,[16] and experimental studies have found that the monomer priming of denture teeth and surface treatment of repair resin both affect strength.[17,18] Other experimental studies indicate that the denture tooth material and cuspal angulations of the embedded tooth affect the pressure transfer capability of the denture

Clinical Implications

This in vitro study suggests that in partially and completely edentulous patients with a reduced interarch distance, a composite resin denture tooth is indicated, and that the acrylic resin denture base layer underneath the tooth bottom should have a thickness of at least 1.0 mm. A ceramic tooth may be contraindicated for a thin denture base because of early chipping.

Table 1. Denture tooth specimens

Type	Brand Name	Manufacturer	Code	Mold	Shade	Lot No.
Acrylic resin	Wearless Acrylic	GC	AC	33M	R3	1209241
Composite resin	Surpass	GC	CO	32M	A3	1210106
Ceramic	Ace Kyushi	Shofu	CE	M31	8	41203

base under impact loading.[19,20] Nevertheless, the selection of denture tooth material and thickness in patients with reduced interarch distance remains controversial, and recommendations have not yet been established.

The purpose of this study was to investigate the influence of the denture tooth material and thickness on the fracture mode of a thin acrylic resin denture base. A single molar denture tooth embedded in a rectangular denture base block of acrylic resin was modeled for the loading experiment and finite element analysis. An analysis of fracture mechanisms is necessary before in vitro testing of material strength can be considered clinically valid. An understanding of the stress distribution in the denture base with an embedded tooth under loading may reveal the underlying fracture mechanism. The hypothesis was that the fracture mode and resistance of the thin acrylic resin denture base would depend on the material and thickness of the tooth.

MATERIALS AND METHODS

Specimen preparation

Each specimen consisted of a mandibular first molar denture tooth embedded in an acrylic resin denture base block. Commercial denture teeth of 3 different materials were used: acrylic resin (AC), composite resin (CO), and ceramic (CE) (Table 1). The base of the AC and CO teeth were ground so that the distance between the central fossa and tooth base was 0.5 mm, 1.0 mm, 2.0 mm, or 2.5 mm (Fig. 1). The same procedure was conducted for CE to obtain a distance of 1.0 mm. For each tooth material, a specimen replica was created by embedding 1 of the polished teeth into a wax block 20 mm long, 12 mm wide, and 2 mm thick.[16] The tooth was placed in the block with the buccolingual surfaces parallel to the length of the block and the mesiodistal occlusal groove parallel to the center of the long axis. The vertical distance from the central fossa to the bottom of the wax block was standardized at 2.5 mm for all specimens. A mold for the replica was made with silicone impression material (Duplicone; Shofu). For each specimen, a polished denture tooth was placed in the mold, and molten wax (Inlay Wax Medium; GC Corp) poured. Each wax block with a

tooth was invested (Advastone; GC Corp), the wax was removed, and a heat-polymerizing denture base material (Acron; GC Corp) was processed at 75°C for 8 hours. Each specimen was then recovered and finished with #600 abrasive paper (DCCS; Sankyo-Rikagaku) to obtain a 2-mm thick block. Seven specimens were made for each material, thickness, and support span combination.[16] The sample size was determined based on the results of a preliminary study, in which a relatively low standard error was observed for one of the thicknesses used.

Fracture test

Each specimen was subjected to a flexural test with axial loading units (Autograph AGS-H; Shimadzu). Each specimen was placed on 2 metal supports of a shorter (8 mm) or a longer (12 mm) span compared to the buccolingual tooth width (approximately 10 mm). A spherical wedge with a 2 mm radius engaged the central groove of each tooth during loading (Fig. 2). The CE specimens were tested by using the longer support. Each specimen was deflected with a vertical crosshead speed of 5 mm/min until fracture occurred. The results were evaluated on a comparative basis with the statistical methods described subsequently and also by comparisons with the reported maximal occlusal force of normal individuals or denture wearers.[21-24]

After the load test, the fractured specimens were observed with optical light microscopy at ×25 magnification (AX70PROVIS; Olympus) to evaluate the fracture initiation site and fracture mode. Some specimens were coated with platinum, and the surface was observed by scanning electron microscopy (S-4500 SEM; Hitachi Ltd).

Nanoindentation test

To determine the material properties of the finite element model of the composite resin denture (CO) specimen, the elastic moduli and hardness of the CO tooth and the acrylic resin denture base materials were measured with a nanoindentation test (ENT-1100a; Elionix). The cross-sectional material surfaces were fine polished to a particle size of 0.06 μm with silicon carbide papers and aluminum oxide slurry. Like most composite resin denture teeth, the CO contains an acrylic resin layer in its lower portion to enhance its bonding capability to the acrylic resin denture base.[25-27] Seven indentation points were arbitrarily selected for each of the denture base, enamel, dentin, and base layers of the CO. The Martens
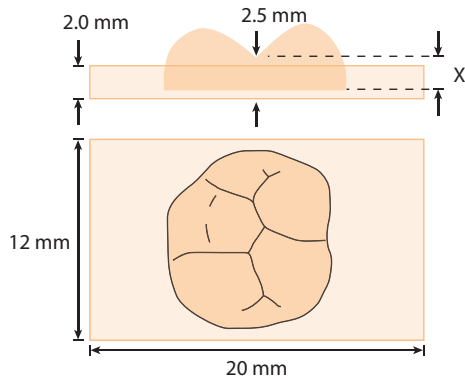
Figure 1. Tested specimens and dimensions. Upper, seen from mesio-distal direction. Tooth thickness (X) was 0.5, 1.0, 2.0, or 2.5 mm. Lower, seen from above.

Figure 2. Three-point flexural loading test. Two different support lengths, 8 mm or 12 mm support length.

hardness and elastic modulus were then measured at a maximum force of 50 mN by using a Berkovich indenter attached to a nanoindentation device. The modulus was calculated in accordance with the following equation, based on the load-displacement curve:

$$Er=\left\{\left(1-vs^2\right)/Es+\left(1-vi^2\right)/Ei\right\}^{-1},$$

where Er is the effective modulus from the nanoindenter, Es is the modulus of the specimen, Ei is the modulus of the indenter, vs is the Poisson ratio for the specimen, and vi is the Poisson ratio of the indenter. To avoid accumulating data from indentations performed on the hard fillers rather than on the matrix, the shape of the indentation, the load-displacement curve, and the range of the hardness data were closely inspected.[28] Table 2 shows the mean Martens hardness and elastic modulus of the CO tooth and the acrylic resin denture base material.

Table 2. Martens hardness and elastic modulus of composite resin tooth and denture base resin

Material	Martens Hardness (GPa), Mean (SD)	Elastic Modulus (GPa), Mean (SD)
Denture base resin	0.17 (0.00)	5.28 (0.06)
Composite resin tooth		
Enamel layer	0.28 (0.03)	6.67 (0.35)
Dentin layer	0.18 (0.00)	5.20 (0.02)
Lower portion	0.19 (0.00)	5.37 (0.10)

Finite element analysis

Three-dimensional finite element models of the 1.0 mm or 2.0 mm thick CO specimens with 2 support spans were constructed to simulate the loading test (Fig. 3). Each model consisted of approximately 170 000 hexahedral elements, as determined by preliminary convergence tests (ANSYS 11.0; ANSYS Inc).[29] All materials were homogeneous, linearly elastic, and isotropic. The mean moduli obtained by the nanoindentation test were entered into the program. The interface between the side tooth surface and the block was assumed to be completely bonded or in contact with a 0.3 friction coefficient. A 0.3 mm vertical displacement was applied at the loading contact. The maximum principal stress distributions in the block were analyzed.

Statistical analysis

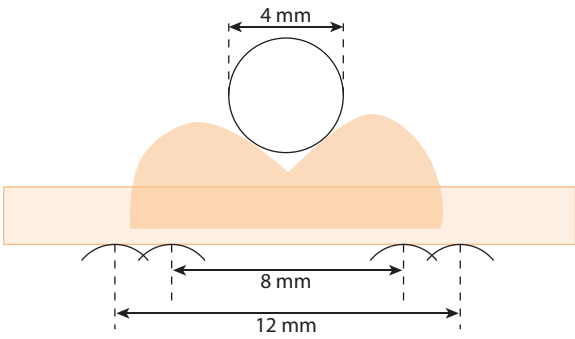Statistical software (SPSS v11.5J for Windows; IBM) was used to detect significant differences in the maximum load between different tooth thicknesses and materials. The data stratified by specimen thickness were compared by 1-way ANOVA. The Tukey honestly significant difference test was used for post hoc analysis when equal variances could not be assumed (α=.05). The Tamhane T2 test was used only for the CO specimens under the shorter support for post hoc analysis because equal variances could not be assumed (α=.05). In addition, the AC and CO specimens were each compared according to support length with 2-way ANOVA.

RESULTS

All the AC and CO specimens exhibited fractures that initiated at the bottom surface of the blocks. The fracture modes were classified into 3 groups as follows (Fig. 4): (1) center-to-tooth mode, in which an initial crack occurred at the center of the bottom surface of the block, followed by the tooth fracture; (2) edge-to-tooth mode, in which the crack occurred at the bottom surface right under the edge of the tooth, the crack subsequently propagating obliquely upward to the center of the occlusal surface; and (3) edge-to-edge mode, in which the crack occurred at the bottom surface right under the edge of the tooth, the crack subsequently propagating vertically upward without a tooth fracture. For all specimens tested on the shorter support, fractures occurred in the center-to-tooth mode. For the longer support, all specimens exhibited fractures in the center-to-tooth or edge-to-tooth modes, except for 9 AC specimens (two 2.0 mm thick and all 2.5 mm thick)
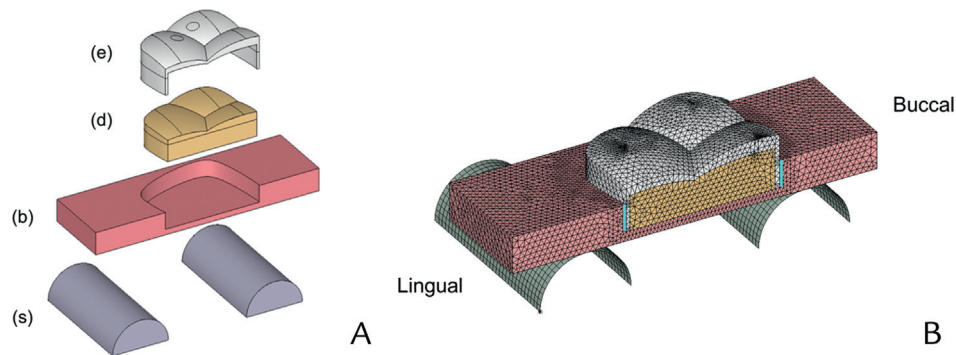
Figure 3. Finite element model descriptions and stress distributions of denture base block. A, Model components in cross-sectioned half views: (e) enamel; (d) dentin; (b) acrylic resin denture base block; and (s) metallic supports. B, Components assembled and meshed to create finite element model. Side surface of (e) was assumed to be bonded or contacted with denture base block (b) (light blue lines).
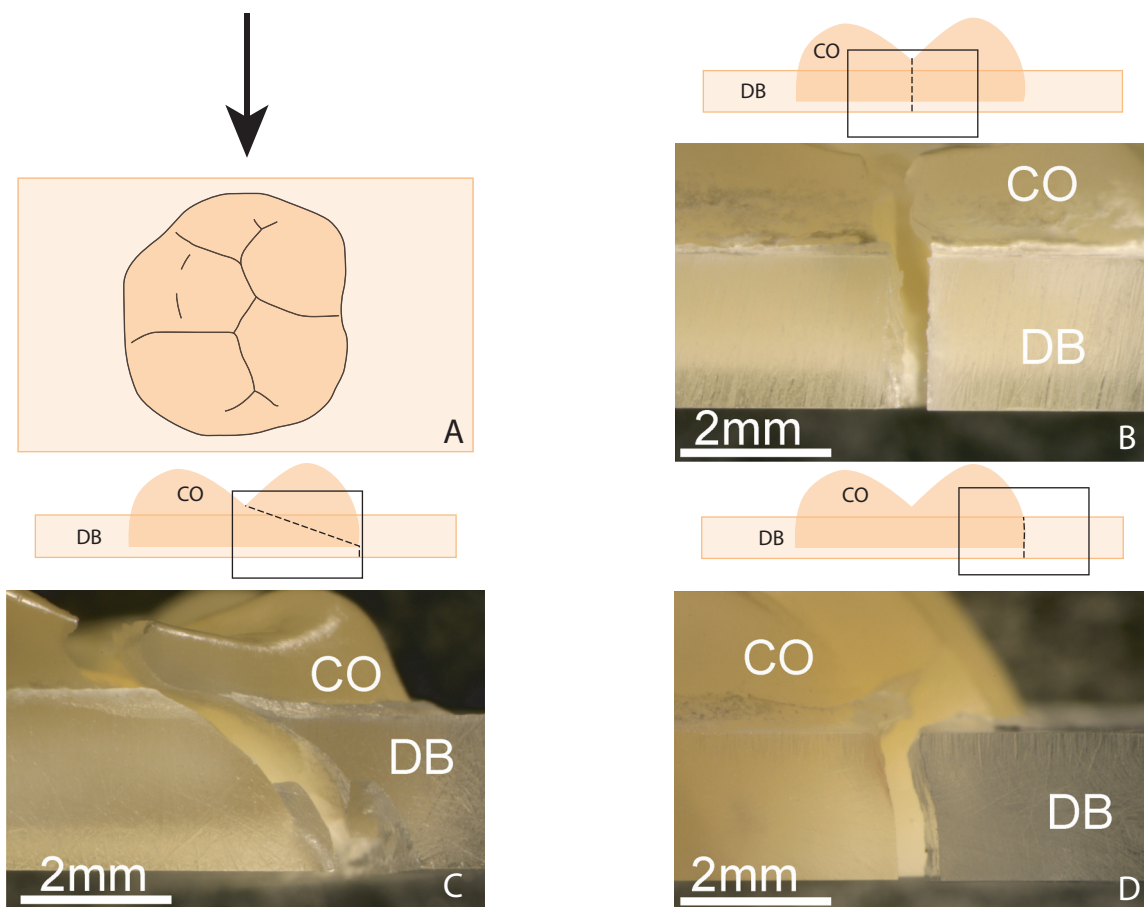

Figure 4. Fracture modes. Dashed line and rectangular area in schematic illustrations of each fracture mode indicate fracture line and the viewing area for optical microscopic image (original magnification, ×25). All representative images were obtained from CO specimens. A, Arrow indicates viewing angle. B, Center-to-tooth fracture mode. C, Edge-to-tooth fracture mode. D, Edge-to-edge fracture mode.

and 5 CO specimens (one 2.0 mm thick and four 2.5 mm thick) that were in the edge-to-edge mode. On the basis of the observations of specimens exhibiting the center-to-tooth mode, most AC specimens cracked at the interface between the side tooth surface and the block, but such cracks were not found in the CO specimens (Fig. 5).

With the shorter support, tooth thicknesses between 0.5 mm and 2.5 mm did not significantly affect the maximum load on the AC and CO specimens (P>.05). However, the mean maximum load was significantly higher in the CO than that in the AC (P<.05) (Fig. 6). Under the longer support, no significant differences were found between the AC and CO specimens (P>.05).
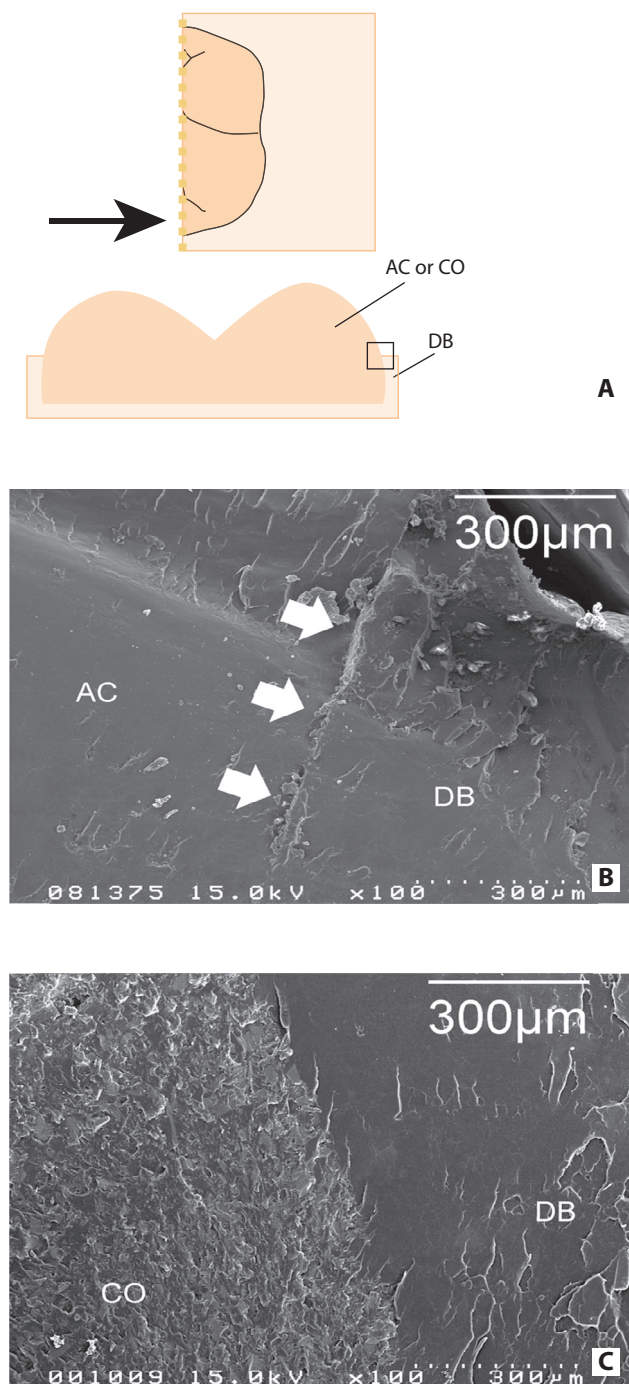
Figure 5. Fracture surface of 2.0-mm thick specimens under center-to-tooth mode. A, Dashed line indicates fracture line, arrow indicates viewing angle, and small black square in lower figure indicates area of SEM images. B, C, Crack lines (white arrows) in (B) occurred at upper interface between tooth edge and denture base block (DB) in all AC specimens; no crack gap was found in CO specimens (original magnification, ×100).

With this support span, the mean maximum load of the CO significantly decreased as the tooth thickness increased from 0.5 mm (962.3 N) to 2.5 mm (450.5 N). In the 2.5 mm thick CO specimens, those showing

the edge-to-edge mode (without tooth fracture) had a significantly lower maximum load than those of the other fracture modes (with tooth fracture) (P<.05) (Fig. 6).

The mean maximum load was significantly higher for the 1.0 mm thick CE specimens (1102.9 ±100.4 N) than the AC and CO of corresponding thickness. However, all CE specimens revealed minor peaks in the load-deflection strip chart, which indicated chipping of the ceramic before catastrophic failure. Chipping damage was found in all CE specimens.

The finite element analysis indicated that the 2 mm thick CO model with the contacted interface had a higher maximum tensile stress at the bottom surface of the block than models embedding the 1 mm thick tooth and those with the bonded interface. In the 2 mm thick contact model, the high stress concentration appeared in the bilateral regions under the tooth edges (Fig. 7).

DISCUSSION

In specimens showing the center-to-tooth fracture mode, the resultant load to failure likely reflects the flexural strength of each tooth material. The higher modulus of the enamel portion of the CO compared to the acrylic resin materials may explain the higher maximum load of the CO specimens compared to AC. With the shorter support span, the load to fracture was insensitive to the tooth thickness. This was because the lower portion of the CO tooth had similar mechanical properties to the acrylic resin denture base, and the material strength at the region near the crack initiation (lower part of the specimens) might be similar in all specimens of different tooth thickness.

The significant decrease in the mean maximum load of the CO as the tooth thickness increased under the longer support span was clearly explained by the stress analysis, which showed that the maximum tensile stress on the bottom surface was higher with the 2.0 mm thick tooth than that with the 1.0 mm thick tooth (Fig. 7). When a thick composite resin denture tooth was in contact with (not bonded to) the denture base, the thin layer of denture base resin between the composite resin edge and rigid metal support was distorted under flexure, creating a high stress concentration (Fig. 7). This scenario did not occur when a thin composite resin tooth was in contact with the thick denture base. The stress was also relieved when the composite resin tooth was perfectly bonded because the high stress could be immediately transferred to the larger specimen volume. The result suggests that the tooth depth within the block determined the fracture mode under the longer support span. This contacted model suggested that a high concentration of stress could be created within the denture base material once bond failure had occurred at the tooth
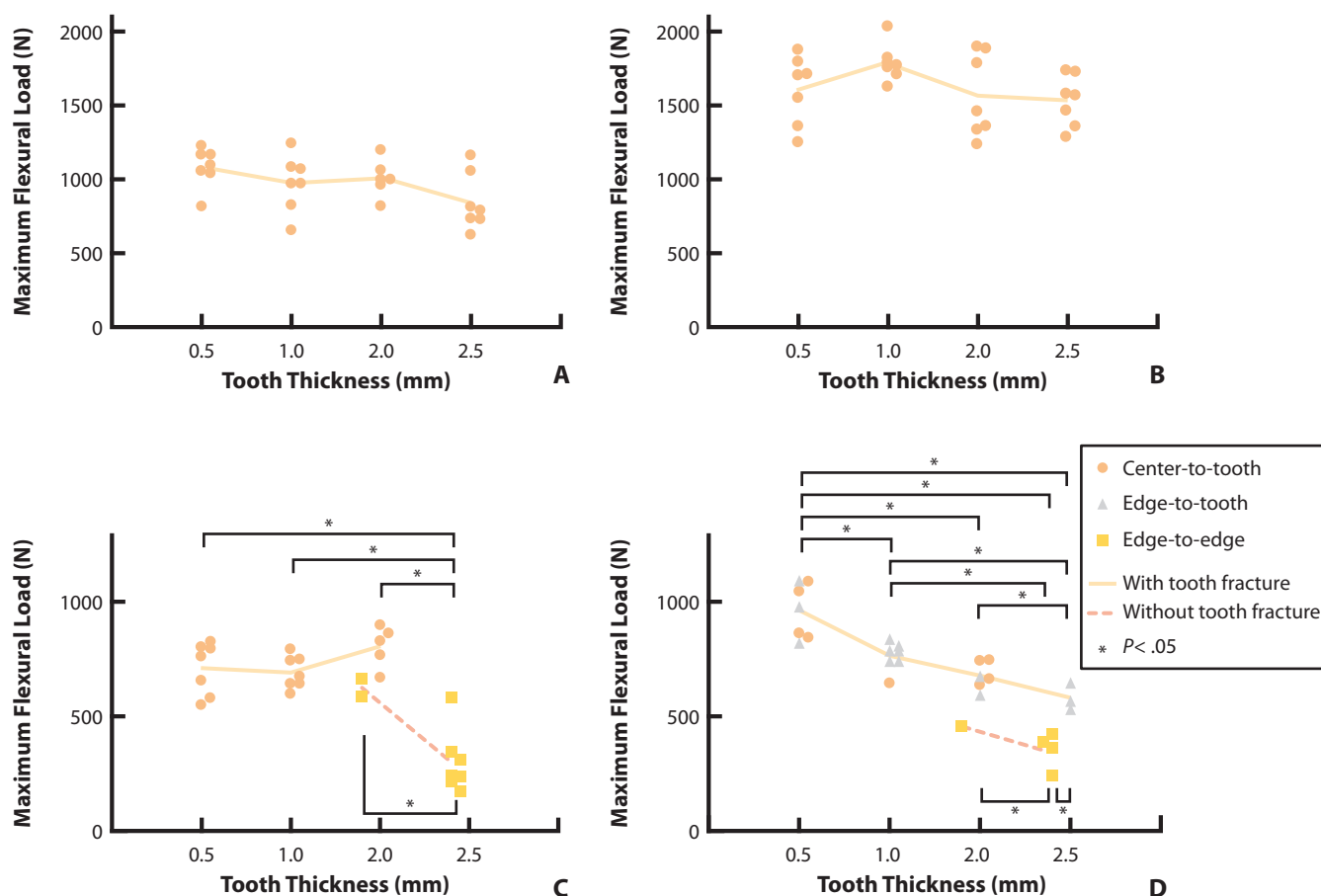
Figure 6. A-D, Maximum load to fracture of acrylic resin block with acrylic (AC) or composite resin (CO) denture tooth on shorter or longer support. A, AC on shorter support. B, CO on shorter support. C, AC on longer support. D, CO on longer support. For fracture mode, 2 groups were compared by statistical analysis; specimens that showed center-to-tooth or edge-to-tooth mode were designated as group with tooth fracture (solid line), and specimens of edge-to-edge mode were categorized as group without tooth fracture (dotted line).

edge. We therefore estimated that when the support span was longer than the tooth width, the bond failure initially occurred at the tooth edge, creating the crack at the bottom of the block and propagating it vertically (edge-to-edge) or obliquely (edge-to-tooth) toward the upper part of the specimen. Because the elastic modulus of the denture base was less than that of the composite resin edge of the denture tooth, local distortion or high strain could occur in the denture base between the composite edge and metal support. This concentrated strain could cause early fracture, beginning at the bottom edge of the specimen.

Edge-to-edge mode without tooth fracture occurred in several 2.0 mm and 2.5 mm specimens under the longer support (shown as orange squares in Fig. 6), with significantly lower load than those under the other fracture modes. Although the lower portion of a composite resin tooth usually consists of an acrylic resin material to enhance the bonding capability to the denture base,[25,26] the side surface is normally not treated for the

bond. The bonded interface area was larger in the specimens with a thicker tooth; therefore, the risk of interfacial failure may have increased, particularly when the bottom surface of the tooth was exposed outside the denture base.

More edge-to-edge fractures occurred in the AC specimens than in the CO specimens. The result was contrary to our expectation because the bond strength between the acrylic resin teeth and the denture base was supposedly better than that between the side surface of composite resin teeth and denture base.[27] We confirmed the weak bond at the tooth edge by the interfacial gap between the AC and acrylic resin block in the specimens of the center-to-tooth fracture mode (Fig. 5). Because only 1 commercial denture tooth brand was used for each tooth material in this study, we cannot conclude that the same result occurs in other denture teeth. However, the bonding capability of the side surface may be important in inducing an acrylic resin fracture in a thin denture base.
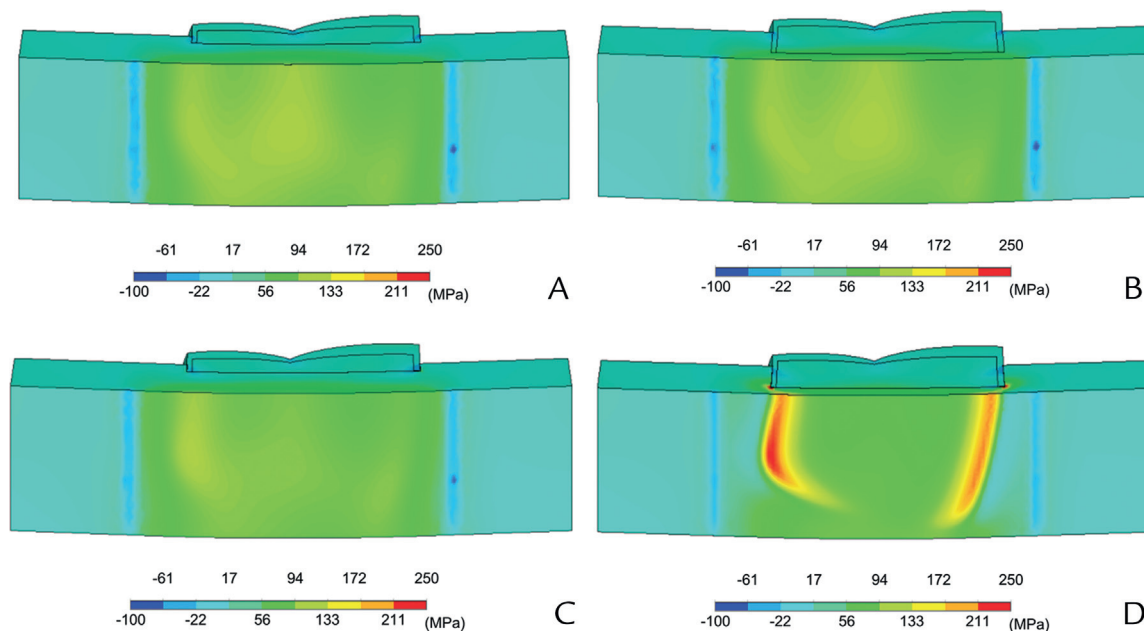
Figure 7. Maximum first principal stress distributions of CO specimen on supports 12 mm in length. Graphics show one-half of each specimen (viewed from bottom). Metallic supports are not shown. Each graphic is divided into 9 parts of different colors, indicating different stress levels (scale below graphic). Red areas indicate highest principal stress level (tensile). A, Bonded model of 1.0 mm tooth thickness. B, Bonded model of 2.0 mm tooth thickness. C, Contacted model of 1.0 mm tooth thickness. D, Contacted model of 2.0 mm tooth thickness.

The results support the hypothesis because the fracture mode and resistance of the thin acrylic resin denture base depended on the tooth material and thickness. In this study design, a support span shorter than the denture tooth was used to simulate a relatively good adaptation of the denture base to the alveolar ridge, whereas the span longer than the tooth width was used to simulate a poor fitting. A limitation of the study was that only 1 type of denture tooth cusp angulation and loading sphere radius were used. In addition to the potential causes of stress concentration in the denture base, such as the position of the denture tooth, denture movement, condition of denture supporting tissues, and occlusal scheme,[6-10] the simulation in this study suggests that the denture fit and the combined mechanical properties of the bone and overlying soft tissues influence the fracture mode and resistance, particularly in patients with a reduced interarch distance.

The CE specimens showed the highest mean maximum fracture load among the different denture tooth groups of corresponding thickness. However, they exhibited ceramic chipping on the occlusal surface at a relatively low load of between 200 and 400 N, which was similar to the maximum occlusal force of normal individuals or implant-supported overdenture wearers.[21-24] The chipping was followed by tooth detachment from the denture base and bulk fracture. Although the effect of the loading sphere should be considered for the evaluation, a ceramic denture tooth may be contraindicated for use with a thin denture base.

CONCLUSIONS

This in vitro experiment with finite element analysis suggested that the fracture resistance of a thin denture base under a support span shorter than the tooth width was higher with a composite resin tooth than with an acrylic resin tooth and that the resistance decreased as the composite resin tooth thickness increased when the support span was longer than the tooth width.

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