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Effects of two types of surface treatments on the structural elasticity of human fingernails

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Abstract

Background: The human nail has a three-layered structure. Although it would be useful to quantitatively evaluate the changes in deformability of the nail due to various surface treatments, few studies have been conducted.

Methods: The effects of two types of surface treatment—a chemically acting nail softener and a physically acting nail strengthener—on the deformability of human fingernails were investigated. The Young's modulus of each plate of the nail samples before and after softening treatment was determined by nanoindentation. The Young's modulus of the strengthener was determined by conducting a three-point bending test on a polyethylene sheet coated with the strengthener.

Results: Young's modulus decreased in order from the top plate against the softening treatment time, and the structural elasticity for bending deformation (SEB) of the nail sample, which expresses the deformability against bending deformation independent of its external dimensions, decreased to 60% after 6 h of treatment. The Young's modulus of the nail strengthener was 244.5 MPa, which is less than 10% of the SEB of the nail. When the nail strengthener was applied to the nail surface, the SEB decreased to 73%, whereas the flexural rigidity increased to 117%.

Conclusion: Changes in nail deformability caused by various surface treatments for softening and hardening were quantitatively evaluated successfully.

KEYWORDS
bending deformation, flexural rigidity, human nail, nail softener, nail strengthener, nanoindentation, structural elasticity, Young's modulus

1 | INTRODUCTION

Nail diseases, such as pincer nails and thickened nails, are serious problems, especially for the elderly, as they are painful and interfere with daily life.[1–3] Pincer nails are corrected mechanically with wires and clips,[4,5] whereas thickened nails are removed using a file to reduce their thickness. Softening treatment[6] is effective for both diseases. In addition, the nail is susceptible to external impact because its surface is exposed, resulting in cracked or split nails. One preventive measure for these problems is to apply a nail strengthener.[7,8] Although it would be useful to quantitatively evaluate the changes in nail deformability due to various surface treatments for softening or hardening the nail, few studies have been conducted.

Human nails have a three-layered structure consisting of top dorsal, middle intermediate, and under ventral plates.[9–11] Therefore, the deformability of a nail depends on the Young's modulus and dimen-

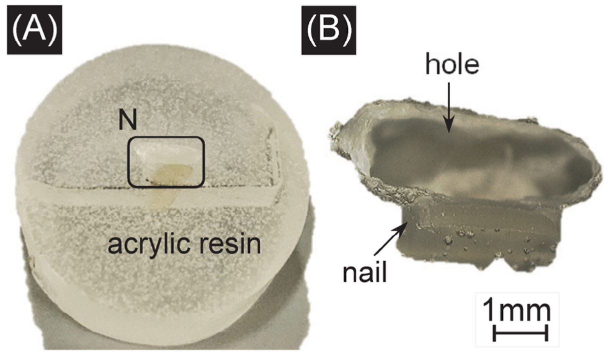

FIGURE 1 (A) Photograph of nail sample, where the nail is embedded in acrylic resin. (B) Details of *N* in (A), where the hole is introduced on the top surface of the nail for softening treatment.

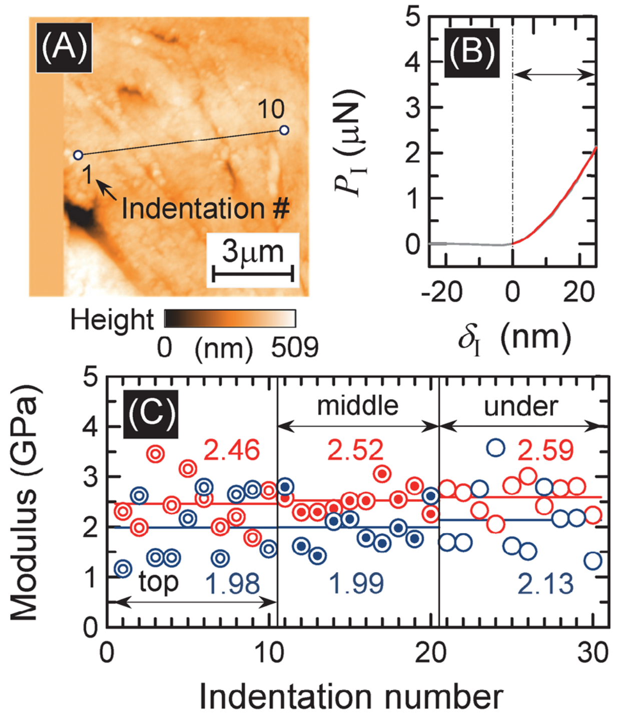

FIGURE 2 Results of nanoindentation (sample N3): (A) AFM image of cross-section of the top plate of the nail sample. (B) Relationship between P_I and δ_I at the position (indentation #6). (C) Young's moduli at each indentation number before (red) and after (blue) softening treatment for 1 h.

sion ratio of each plate. Considering this three-layered structure, the structural elasticity for bending (SEB) of the nail has been proposed as an index of its bending deformation independent of the external dimensions.[12] The unit for SEB is Pa, which is the same as that of the Young's modulus for homogeneous materials. Human hairs also have a three-layered structure consisting of outer cuticle, middle cortex, and inner medulla layers,[13] and the SEB of the hair has been proposed.[14] A previous study proved that the nail bends more easily than hair by comparing the SEB of a nail with that of hair.[15]

This study reports a quantitative evaluation of changes in the SEB of nail samples subjected to two types of surface treatments. The first is a softening treatment that uses a chemically acting softener. Temporal changes in the SEB of the nail were investigated after the softener was applied to its surface. The other is a physically acting nail strengthener. The Young's modulus of the nail strengthener was determined by conducting a three-point bending test on a polyethylene sheet coated with the strengthener. The SEB and flexural rigidity (FR) of the nails with and without nail strengthening were quantitatively estimated.

2 | MATERIALS AND METHODS

In this study, the Young's modulus of each plate of fingernail samples before and after softening treatment was determined by nanoindentation, and the changes in SEB over time for the softening treatment were investigated.

2.1 | Fingernail samples and softening treatment

Nail samples were collected from the fingernails of an Asian male in his 20s. First, masking tape, rounded into a cylindrical shape of 1–2 mm in diameter, was attached to the surface of the nail sample, which was then embedded in an acrylic resin (KM-U, PRESI). After cutting the cross-section of the embedded sample with a precision cutter, the tape was removed, and a hole was introduced into the resin for the softening treatment. The embedded samples were then polished with abrasive paper and finally finished with a 0.25 mm diamond slurry. A photograph of a nail sample is shown in Figure 1A. The details of *N* in Figure 1A are shown in Figure 2B, and the hole in which the softener was placed was introduced on the top surface of the nail. The softener used in this experiment was a cream containing 20% urea (Keratinamin Kowa, Kowa). The softener was then placed in the hole for treatment; after the prescribed treatment time, the cream was removed from the hole, and nanoindentation was performed. Nine samples were prepared, and the Young's modulus of each plate was determined by nanoindentation using the method described in the next section for determining the SEB of the sample (see Appendix A1). The softening times of samples N1–N3, N4–N6, and N7–N9 were 1, 3, and 6 h, respectively.

2.2 | Nanoindentation

Nanoindentation is a suitable tool for locally measuring the Young's modulus of a sample and is widely used in the mechanical characterization of human nails.[16,17] In this study, an atomic force microscope (FlexAFM, Nanosurf) and a cantilever with a cone-shaped probe tip (Tap190A1-G, BudgetSensors) were used for nanoindentation. The experimental procedure for determining the Young's modulus of each plate by nanoindentation was the same as that used in our previous study.[12] The force curve while pulling the probe up was recorded to determine the Young's modulus of each plate. From the obtained relationship between the force (P_I) and displacement (δ_I), the Young's modulus at the point was determined using Equations (A5)–(A7) based on the Hertzian model (see Appendix A3). In this study, the ν value for the nail samples was assumed to be 0.30.[18]

2.3 | Three-point bending test of two-layered beam

To determine the Young's modulus of the nail strengthener (Nail Envy NTT80-JP, OPI), a three-point bending test was performed on a two-layered beam. First, a three-point bending test was performed on a polyethylene sheet with a height (h) of 40 μm and width (b) of 1 mm as the substrate to obtain the load–displacement (P_B–δ_B) relationship. The distance between two simple supports (L) was 1.73 mm, and a load was applied in the middle of two supports. From this relationship, the Young's modulus of the polyethylene sheet (E_2) can be determined using the following equation:

$$P_B = \frac{48E_2 I}{L^3}\,\delta_B, \tag{1}$$

where I ($=b\,h^3/12$) is the moment of inertia of the sample with a rectangular cross-section. Next, a polyethylene sheet was coated with a nail strengthener, and a three-point bending test was performed on this two-layered beam. The relationship between P_B and δ_B for this two-layered beam can be obtained by replacing E_2 with SEB for the two-layered structure shown in Equations (A3) and (A4) (see Appendix A2). Finally, the Young's modulus of the nail strengthener (E_1) was determined from E_2, SEB, and Equations (A3) and (A4). The testing apparatus used for the three-point bending test was previously developed by the authors for bending tests of human hair.[19] A total of five samples (H1–H5) were prepared. The three-point bending test was conducted on the samples 24 h after the nail strengthener was coated on the sheet.

3 | RESULTS AND DISCUSSION

3.1 | Time change in structural elasticity of nail samples by softening treatment

An example of the experimental results of the nanoindentation of sample N3 is shown in Figure 2. Figure 2A shows an AFM image of the top plate, and the indentation number where the nanoindentation was performed is shown in the image. Nanoindentation was performed at 10 points for each plate. Figure 2B shows the relationship between P_I and δ_I at indentation #6. In this relationship, the data over $\delta = 0$ nm were fitted to Equation (A7) to determine the Young's modulus at that point. The relationship between P_I and δ_I was given by $P_I = 5.337 \times 10^5\,\delta_I{}^{3/2}$, and the Young's modulus was determined to be 2.56 GPa, where the value of R was 20.18 nm. Figure 2C shows the Young's moduli against indentation number. In sample case (N3), the values of E_1, E_2, and E_3 before softening treatment (red) were 2.46, 2.52, and 2.59 GPa, respectively. The values of Young's modulus of each plate after 1 h of softening treatment (blue) are also shown in Figure 2C, and the values of E_1, E_2, and E_3 decreased to 1.98, 1.99, and 2.13 GPa.

The Young's moduli of each plate before and after the softening treatment and the SEB values determined using Equations (A1) and (A2) are summarized in Table 1. The change in the rate of decrease of each plate, which is defined by the ratio of the Young's modulus after the softening treatment to that before the treatment in percentage representation, against time for the softening treatment, is shown in Figure 3A. After 1 h of treatment, the Young's moduli of the top (E_1), middle (E_2), and under plates (E_3) decreased to 77%, 86%, and 94%, respectively, indicating a significant softening effect, especially in the top plate. In contrast, the Young's moduli of the top, middle, and under plates after 6 h of treatment decreased to 60%, 59%, and 59%, respectively, indicating similar softening effects in each plate. This suggests that it took 6 h for the softener to fully penetrate the under plate. The change in the decrease rate of SEB is shown in Figure 3B. In this estimation, the ratio of the thicknesses of the top, middle, and under plates is assumed to be 3:5:2.[11] The value of SEB after 6 h

TABLE 1 Changes in Young's modulus of each plate of the nail samples with treatment time.

Sample	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	SEB (GPa)
Before softening treatment				
N1	2.83 ± 0.34	2.93 ± 0.29	2.77 ± 0.29	2.82
N2	2.20 ± 0.39	2.54 ± 0.34	2.17 ± 0.32	2.24
N3	2.46 ± 0.50	2.52 ± 0.24	2.59 ± 0.29	2.52
Avg.	2.50 ± 0.26	2.66 ± 0.19	2.51 ± 0.25	2.53 ± 0.24
After softening treatment for 1 h				
N1	2.02 ± 0.58	3.12 ± 0.67	2.77 ± 0.55	2.44
N2	1.74 ± 0.45	1.75 ± 0.44	2.21 ± 0.59	1.92
N3	1.98 ± 0.64	1.99 ± 0.42	2.13 ± 0.68	2.04
Avg.	1.91 ± 0.13	2.29 ± 0.60	2.37 ± 0.29	2.13 ± 0.22
Before softening treatment				
N4	3.05 ± 0.67	2.98 ± 1.09	2.60 ± 0.90	2.86
N5	2.77 ± 0.77	2.90 ± 1.13	2.28 ± 0.96	2.59
N6	2.73 ± 0.59	2.97 ± 1.24	2.81 ± 0.63	2.80
Avg.	2.85 ± 0.15	2.95 ± 0.04	2.56 ± 0.22	2.75 ± 0.12
After softening treatment for 3 h				
N4	1.75 ± 0.68	1.93 ± 0.71	1.66 ± 0.72	1.74
N5	1.73 ± 0.66	1.75 ± 0.46	2.02 ± 0.71	1.84
N6	1.76 ± 0.50	1.76 ± 0.68	1.91 ± 0.58	1.82
Avg.	1.75 ± 0.01	1.81 ± 0.09	1.86 ± 0.15	1.80 ± 0.05
Before softening treatment				
N7	2.68 ± 0.65	3.06 ± 0.81	2.69 ± 0.74	2.74
N8	2.59 ± 0.76	2.68 ± 0.57	2.57 ± 0.79	2.60
N9	2.90 ± 0.60	3.02 ± 0.74	2.65 ± 0.71	2.87
Avg.	2.72 ± 0.13	2.92 ± 0.17	2.64 ± 0.05	2.72 ± 0.09
After softening treatment for 6 h				
N7	1.75 ± 0.72	2.07 ± 0.65	1.80 ± 0.59	1.81
N8	1.70 ± 0.40	1.56 ± 0.57	1.49 ± 0.74	1.60
N9	1.42 ± 0.55	1.54 ± 0.66	1.39 ± 0.41	1.42
Avg.	1.62 ± 0.15	1.73 ± 0.25	1.56 ± 0.18	1.61 ± 0.16

Note: E_1, E_2, and E_3 are the Young's moduli of the top, middle, and under plates, respectively. The SEB was determined using Equations (A1) and (A2).

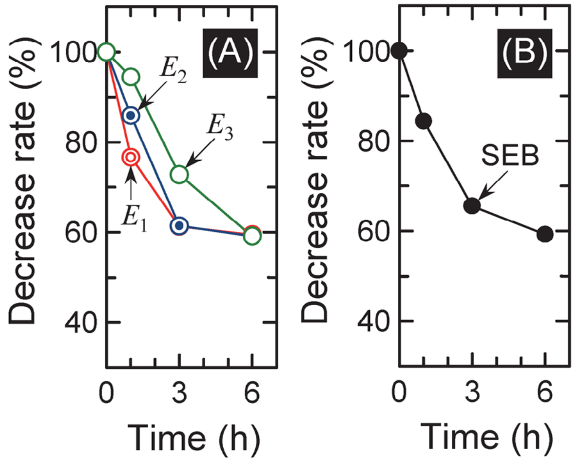

FIGURE 3 Results of softening treatment: (A) Decrease rate of Young's modulus of each plate against the time for softening treatment, and (B) that of SEB. SEB, structural elasticity for bending deformation.

of treatment was 1.61 GPa, which is approximately 60% of the SEB before the softening treatment (2.72 GPa). In our previous study, the same softener was used to examine the change in the SEB, and SEB after 24 h of treatment decreased to 68% of SEB before the softening treatment.[12] These results suggest that, for the case of the softener used in this study, the decrease in SEB of the nail saturates after 6 h of treatment.

3.2 | Young's modulus of nail strengthener and reinforcement effect

The experimental setup for the three-point bending test to determine the Young's modulus of the nail strengthener is shown in Figure 4A. Here, the load (P_B) was applied to the polyethylene sheet in the middle of two simple supports. An example of the relationship between P_B and the displacement (δ_B) of the polyethylene sheet (sample H1) and the sheet coated with the nail strengthener is shown in Figure 4B. Figure 4C shows the relationships between P_B $L^3/(48I)$ and δ_B of the polyethylene sheet with and without nail strengthener. The slope of the relationship without the nail strengthener yields the Young's modulus of the polyethylene sheet ($E_2 = 390.6$ MPa), and that with the nail strengthener yields the SEB of the two-layered beam (285.1 MPa). In this sample case, the value of $\varkappa h$ determined by optical microscopy was 36.9 μm. From the values of E_2, SEB, $\varkappa h$, and Equations (A3) and (A4), the Young's modulus of the nail strengthener (E_1) was determined to be 216.6 MPa. The experimental results for the five samples (H1–H5) are summarized in Table 2. The average value of the Young's moduli of the nail strengthener was 244.5 ± 19.7 GPa, which is less than 10% of that of the nail.

Let us quantitatively estimate the effect of reinforcement, that is, SEB and FR, when the top surface of the nail is coated with the nail strengthener. The SEB of the nail was 2.67 GPa, which was the average value of the SEB of samples N1 to N9 before the softening treatment. The nail thickness, as observed using an optical microscope, was 432.4 ± 24.1 μm. For simplicity, we assume that $b = h$ and obtain FR as 7.77×10^{-6} Pa m^4. The model of the two-layered structure shown in Figure A1B was adapted to estimate the SEB and FR after coating the nail with nail strengthener. The thickness of the nail strengthener was assumed to be 54.4 μm, which is the average value of $\varkappa h$ listed in Table 2. Therefore, the thickness of the nail after coverage with the nail strengthener was $h = 486.8$ μm ($\varkappa = 0.112$). The SEB and FR values of nails with and without nail strengthener are shown in Figures 5A and B, respectively. The SEB of the nail with nail strengthener was 1.95 GPa, which was reduced to 73% by applying the strengthener with a smaller Young's modulus ($E_1 = 244.5$ MPa), whereas the FR increased to 9.13×10^{-6} Pa m^4, an increase of 117%. From this estimation, we found that

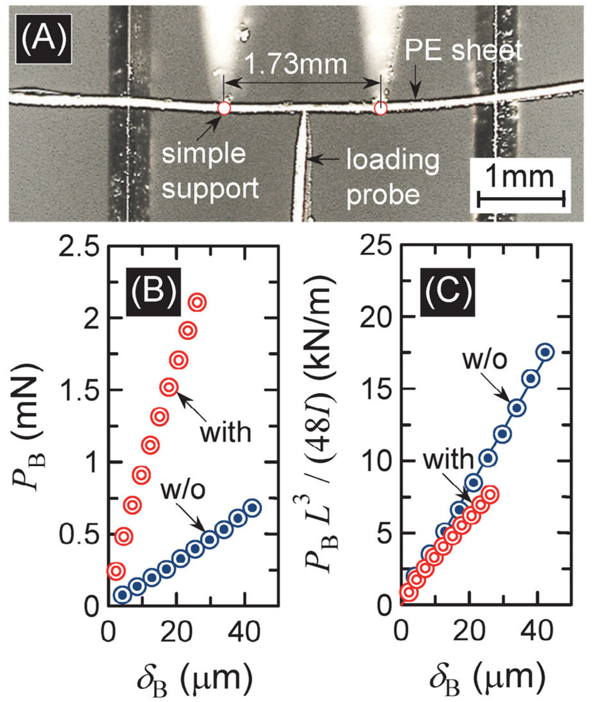

FIGURE 4 (A) Experimental setup for three-point bending test of polyethylene (PE) sheet. (B) P_B versus δ_B, and (C) P_B L^3 / (48 I) versus δ_B of the PE sheet with and without nail strengthener (sample H1).

TABLE 2 Young's modulus of polyethylene sheet without and with nail strengthener.

Sample	E_2 (MPa)	SEB (MPa)	$\varkappa h$ (μm)	E_1 (MPa)
H1	390.6	285.1	36.9	216.6
H2	460.0	317.5	86.4	232.9
H3	398.7	308.6	45.9	245.9
H4	437.1	324.0	71.3	251.4
H5	433.2	341.1	31.8	275.6
Avg.	423.9 ± 25.7	315.3 ± 18.5	54.4 ± 21.0	244.5 ± 19.7

Note: E_1 and E_2 are the Young's moduli of the nail strengthener and polyethylene sheets, respectively. The SEB was determined using Equations (A3) and (A4).

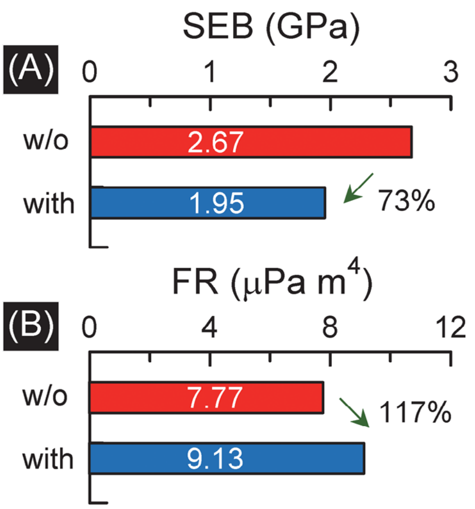

FIGURE 5 Comparison of (A) SEB and (B) FR of the nail with and without nail strengthener on top of the nail surface. The thicknesses of the nail and nail strengthener were assumed to be 432.4 and 54.4 μm, respectively. SEB, structural elasticity for bending deformation.

the nail strengthener with a smaller Young's modulus, in addition to protecting the nail from external impact, also increased the resistance against bending deformation.

4 | CONCLUSION

The effects of the two types of surface treatments on the bending deformation of the human fingernails were investigated. The first was a chemically active nail softener containing 20% urea. The softener was attached to the surface of the nail samples, and the change in the Young's modulus of each plate was determined by nanoindentation after 1 to 6 h of treatment. The results showed that the Young's modulus decreased from the top plate to the softening treatment time, and each plate softened to approximately 60% of the same level after approximately 6 h of treatment. The structural elasticity for bending deformation (SEB) of the nail sample, which expresses the deformability against bending deformation independent of its external dimensions, decreased to 60% after 6 h of treatment. The other surface treatment was a physically acting nail strengthener. First, a polyethylene sheet coated with a nail strengthener was subjected to a three-point bending test, and the Young's modulus of the strengthener was determined. The Young's modulus of the nail strengthener was 244.5 MPa, which is less than 10% of the SEB of the nail. The average thickness of the nail sample observed by an optical microscope was 432.4 μm, and the SEB and flexural rigidity (FR) were estimated when the thickness of the nail strengthener applied on the surface of the nail was 54.4 μm. When the nail strengthener was applied to the nail surface, the SEB decreased to 73%, whereas the FR increased to 117%. The nail strengthener contributed to both the protection of the nail from outer impact and the improvement of its stiffness against bending deformation, as quantitively demonstrated.

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available upon request from the corresponding author.

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APPENDIX

Structural elasticity for bending deformation of three-layered structure

A three-layered structure with a rectangular cross-section is shown in Figure A1A. The height and width of the structure are h and b, respectively. The dimensionless parameters κ and λ denote the dimensions of each layer, and η denotes the position of the neutral axis (n.a.) from the centroid (G). E_1, E_2, and E_3 represent the Young's moduli of the top, middle, and under layers, respectively. The SEB of the three-layered structure is given by[12]

$$\begin{aligned}\mathrm{SEB} = 4E_1\left\{\left[\kappa-\left(\tfrac{1}{2}+\eta\right)\right]^3-\left[-\left(\tfrac{1}{2}+\eta\right)\right]^3\right\}\\ +4E_2\left\{\left[\lambda-\left(\tfrac{1}{2}+\eta\right)\right]^3-\left[\kappa-\left(\tfrac{1}{2}+\eta\right)\right]^3\right\}\\ +4E_3\left\{\left[1-\left(\tfrac{1}{2}+\eta\right)\right]^3-\left[\lambda-\left(\tfrac{1}{2}+\eta\right)\right]^3\right\},\end{aligned} \tag{A1}$$

and

$$\eta h = \frac{1}{2}\left[\frac{E_1\kappa^2+E_2\left(\lambda^2-\kappa^2\right)+E_3\left(1-\lambda^2\right)}{E_1\kappa+E_2(\lambda-\kappa)+E_3(1-\lambda)}-1\right]h. \tag{A2}$$

Structural elasticity for bending deformation of two-layered structure

The two-layered structure with a rectangular cross-section is shown in Figure A1B. The height and width of the structure are h and b, respectively. The dimensionless parameter κ denotes the dimensions of the top layer, and η denotes the position of the neutral axis (n.a.) from the centroid (G). E_1 and E_2 represent the Young's moduli of the top and under layers, respectively. The SEB of the two-layered structure can be obtained by substituting $\lambda = 1$ into Equations (A1) and (A2) as follows:

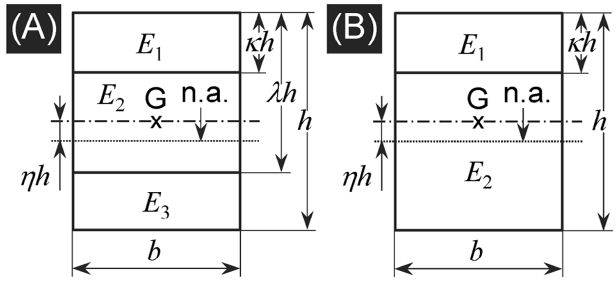

FIGURE A1 (A) Three-layered and (B) two-layered structures having rectangle cross-sections. The height and width of the structure are h and b, respectively.

$$\begin{aligned}\mathrm{SEB} = 4E_1\left\{\left[\kappa-\left(\tfrac{1}{2}+\eta\right)\right]^3-\left[-\left(\tfrac{1}{2}+\eta\right)\right]^3\right\}\\ +4E_2\left\{\left[1-\left(\tfrac{1}{2}+\eta\right)\right]^3-\left[\kappa-\left(\tfrac{1}{2}+\eta\right)\right]^3\right\},\end{aligned} \tag{A3}$$

and

$$\eta h = \frac{1}{2}\left[\frac{E_1\kappa^2+E_2\left(1-\kappa^2\right)}{E_1\kappa+E_2(1-\kappa)}-1\right]h. \tag{A4}$$

Hertz model for nanoindentation

The Hertz model was adapted for nanoindentation in this study, and the relationship between P_I and δ_I for this model is given by

$$P_I = E^* R^{\frac{1}{2}}\delta_I^{\frac{3}{2}}, \tag{A5}$$

where R is the radius of curvature of the probe tip and E^* is the reduced modulus. If the Young's modulus of the probe is sufficiently higher than that of the sample, E^* is given by:

$$\frac{1}{E^*} = \frac{3\left(1-\nu^2\right)}{4E}, \tag{A6}$$

where ν and E are the Poisson's ratio and Young's modulus of the sample, respectively. From Equations (A5) and (A6), E can be determined as follows:

$$E = \frac{3\left(1-\nu^2\right)P_I}{4R^{\frac{1}{2}}\delta_I^{\frac{3}{2}}}. \tag{A7}$$