

THE RIGIDITY OF HUMAN FINGERNAILS: A BIOPHYSICAL INVESTIGATION ON INFLUENCING PHYSICAL PARAMETERS

B. Forslind, G. Nordström, D. Toijer and K. Eriksson¹

Department of Medical Biophysics, Karolinska Institutet, and ¹Department of Strength of Materials and Solid Mechanics, The Royal Institute of Technology, Stockholm, Sweden

Abstract. (A) The property of withstanding bending and buckling in a composite material such as the nail is best described by such terms as rigidity or stiffness. (B) The physical property of rigidity can be understood from the macromolecular orientation of the keratin filaments and the cellular architecture of the dorsal and ventral nail plates. (C) The rigidity is influenced by factors such as the water content of the nail material. Specimens investigated must therefore be well equilibrated prior to the measurements. (D) Detergents, organic solvents, oils etc. are factors which are likely to influence nail rigidity.

Objective data on the mechanical properties of human fingernails are scarce. Few attempts to determine the 'hardness' of fingernails have been reported (1, 7, 8). In clinical reports, strict definitions of the concepts introduced are lacking at present, however, as are also their relationship to the cellular and macromolecular organization of the nail. Effects of previous contacts with solvents, oil, water, etc. are awaiting their due consideration.

Nails are subjected to bending forces when used in everyday life. The nail material, keratin, is a complex structure of macromolecular protein fibres, orientated perpendicularly to the growth direction of the nail and embedded in a non-structural protein matrix (2). This means that the related mechanical property is an effective bending rigidity. In previous studies on the physical properties of human fingernails a tentative explanation of their rigidity was suggested, based upon morphological and biophysical data (2). Further evidence for the validity of the proposed structure-rigidity relationship has been presented (4).

In the present work, important problems in determining the rigidity of the nail have been identified. An effective elastic modulus of the nail material, independent of the dimensions of a particular nail specimen, is introduced. With the method pre-

sented the effects of various treatments upon the effective elastic modulus can be studied. Some examples illustrate the sensitivity of the method. The development of improved methods in determining the mechanical properties of nails is a challenging subject which may provide insight into the changes which take place in nails in health and disease.

MATERIAL AND METHOD

Human fingernail clippings were obtained from 11 persons. The nail clippings (Fig. 1) were obtained either directly or after soaking the fingertips in water. In one case the clippings were collected over about 10 years. A randomized choice of the latter was made in the present work. The clippings were equilibrated for maximum water absorption by immersion in distilled water. Exposure to relative humidities of 79.0, 72.1 and 64.3% obtained in desiccators containing various saturated salt solutions was another means of controlled water absorption of nails. The dehydration of nail clippings was performed by drying for 1 hour at 90°C and subsequently at 60°C for 14 days.

From the clippings $1 \times 5 \times t$ (mm) specimens were cut, where t is the thickness of the clippings. The long axis of the specimens was either parallel or perpendicular to the growth axis (x -axis) of the nail (Fig. 1). In a three-point-bend loading device the specimen was supported at each end by a bar with a circular cross section (0.5 mm diameter). A loading hook was applied at the mid-section of the specimen (Fig. 2). The specimen was loaded by applying known weights to the hook. The deflection of the load point was measured with a microscope to within ± 0.005 mm (Fig 2). During one experiment the deflection was determined as a function of the applied load and/or time.

The initial part of the load-deflection relationship was linear (Fig. 3). This means that the bending rigidity of the nail is constant and that an effective elastic modulus, E_{eff} , can be defined in this range. E_{eff} was

$$E_{\text{eff}} = \frac{P \cdot l^3}{48 \cdot I \cdot \delta_p}$$

where P is the load applied to the specimen (N); l , the effective length of the specimen (m); δ_p , the effective

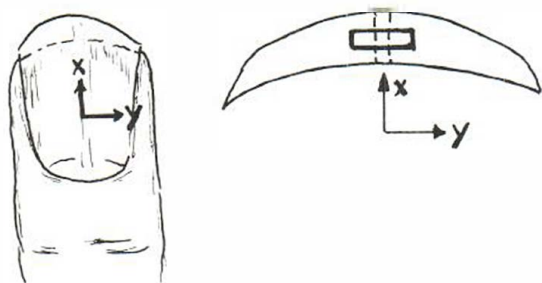


Fig. 1. Diagram of a fingernail and a fingernail clipping showing the two orientations used (solid and stippled box).

deflection of the specimen due to the load P (m); I , the moment of inertia of the cross-section of the specimen. Here $I = b \cdot t^3 / 12$; b , the specimen width, and t , as above, the specimen thickness (m).

The load point deflection

The specimens were slightly curved in the unloaded state. By assuming that the radius of curvature of a specimen is constant for a given load, the effective deflection and effective length of the specimen between the points of

support for a given load P can be calculated as follows. Let

$\delta(P)$ be the observed deflection, i.e. the vertical distance: reference line—loading point, L , the horizontal distance between the centres of the supporting bars, r , the radius of the supporting bars, $\delta''(P)$ the vertical distance: supporting points—loading point, $\delta'(P)$ the vertical distance: reference line—supporting points, $l(P)$ the effective specimen length.

Then

$$\delta''(P) = \delta(P) - \delta'(P)$$

$$\delta'(P) = r(1 - \cos \alpha(P))$$

$$l(P) = 2\alpha(P) \{ \delta(P) / (1 - \cos \alpha(P)) - r \}$$

where

$$\alpha(P) = 2 \arctan (2\delta(P)/L).$$

The effective deflection of the specimen due to the load P is

$$\delta''(P) = f(\delta) - f(\delta_0)$$

where $f(x) = x + r \cos (2 \arctan (2x/l))$.

and $\delta_0 = \delta(0)$, that is, the observed deflection for the specimen unloaded, and

$$\delta = \delta(P).$$

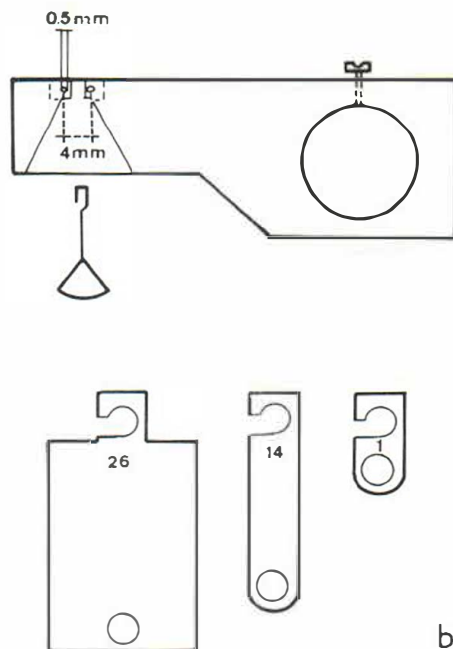
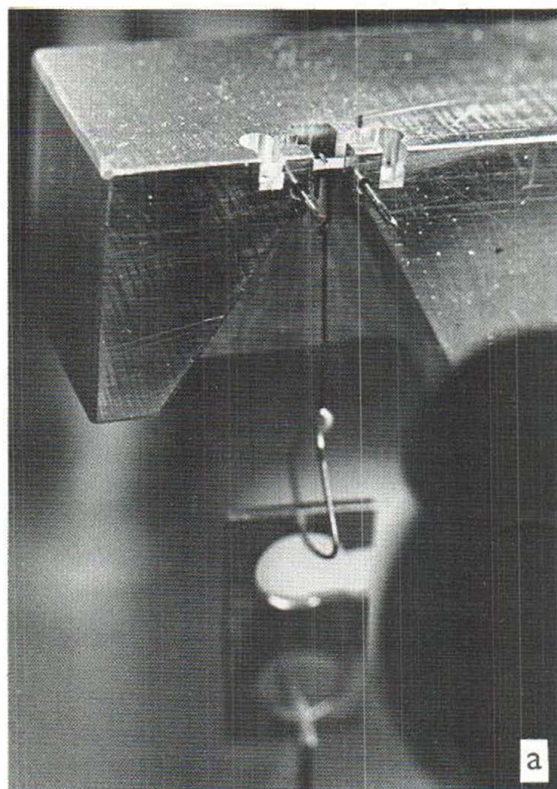


Fig. 2. (a) Loading device with specimen under load. Hook and two weights are seen under the specimen. (b) Loading device (top) and weights (bottom). Stainless steel bars with circular cross section, 0.5 mm \varnothing , support specimen loaded by means of hook and weights attached.

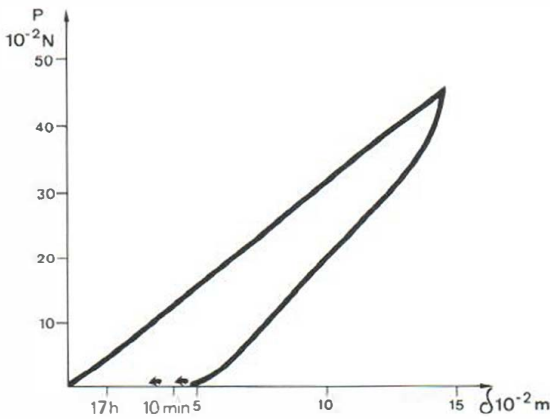


Fig. 3. Load-deflection diagram. Application of increasing load (vertical axis) results in bending of nail specimen (horizontal axis). After complete deloading a complete recovery is not attained within 17 h.

RESULTS

The load was applied step-wise by successive addition of weights. Approximately 15 min was required to cover the linear part of the load-deflection relationship. The entire load was then removed in one step and the deflection subsequently decreased non-linearly. The main part of the recovery occurred within a small fraction of the loading time. However, the complete recovery to zero deflection required more than 17 hours (Fig. 3).

The deflection of the nail at a constant load ($0.9N$) was measured as a function of time during 15 hours. Immediately after loading and during the first 2 hours the deflection increased non-linearly. However, after 2 hours the rate was approximately constant (Fig. 4).

When nail clippings were subjected to extreme loads ($1-1.5N$, or $100-150$ g) a linear loading behaviour was recorded. For even greater loads a non-linear phase with a decreasing tendency occurred (Fig. 5).

When the E_{eff} modulus was plotted against specimen thickness and width, no effect of these parameters on the E_{eff} modulus was recorded, as expected. The E_{eff} modulus was further found to be independent of the radius of curvature in the nail specimens. Neither was it affected by the direction of the curvature, that is, if the specimen was applied in the loading device with the convex side upwards or downwards.

The E_{eff} modulus was directly dependent on the

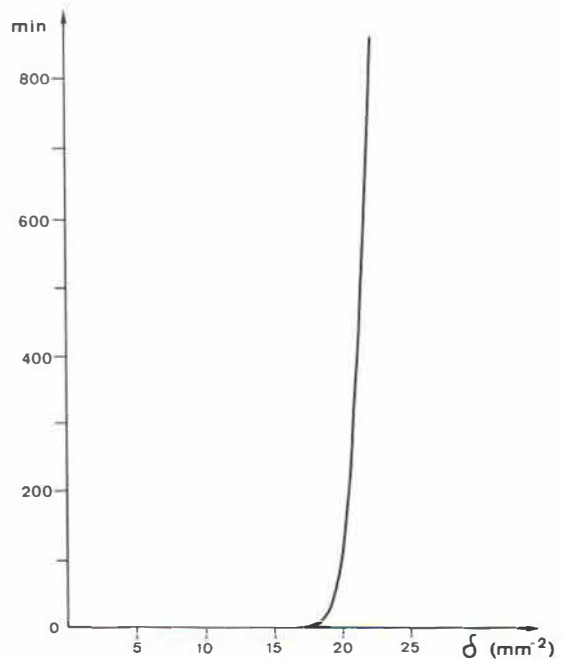


Fig. 4. Deflection of nail specimen at constant load ($0.9N$) as a function of time. After 2 h the deflection rate was approximately constant.

water content of the specimen. This was shown by using specimens equilibrated to fixed values of relative humidity (79%, 72.1% and 64.3%) during at least 14 days, specimens immersed in distilled water, fresh specimens, and oven-dried specimens (Fig. 6).

Pilot studies on the effect of organic solvents, acetone and trichloro-ethylene, tensides, formaline, mineral and vegetable oils, and a commercial nail strengthening fluid were carried out (Fig. 7). All were short-term studies and the results cannot be interpreted uniquely. However, one of us (G. N.) treated his own nails with a commercial preparation for 6 weeks with the result that the mean value of the E_{eff} modulus increased during this time (Fig. 8).

DISCUSSION

Previous works have described the cellular architecture and the macromolecular organization of the nail (2, 3, 5). A tentative description of the expected physical behaviour of the nail plate on bending (2) has been presented and given further support by studies on nail substance behaviour in cutting experiments (4).

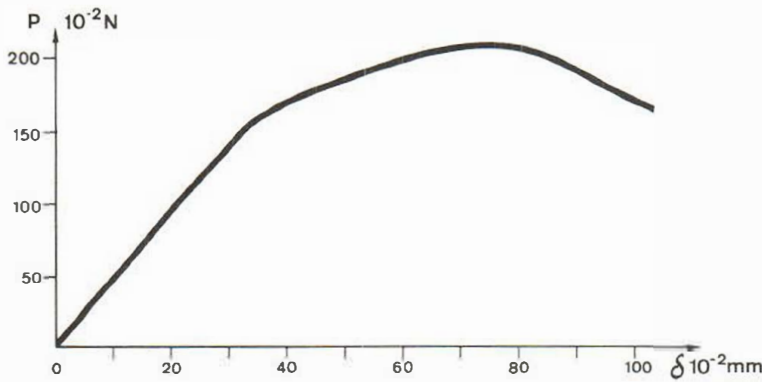


Fig. 5. Loading behaviour for nail at extreme loads. Note the non-linear response at loads greater than 1.5 N.

A complex structure like the nail is likely to show a complex behaviour under load. In analogy with fibre-reinforced plastics, we expect the material to be visco-elastic. This means that a sudden loading of the specimen would result in an immediate, elastic response, but deformation will continue with time. As the immediate response is entirely linear, a constant elastic modulus can be defined, which applies to the linear range of the load-deformation relationship. Since the elasticity is most likely to vary in the thickness direction of the nail, we have limited ourselves to determining an effective elastic modulus of the nail material, rather than the proper distribution.

It is interesting to see that the natural curvature of the nails does not affect the effective elastic modulus of the nail. Neither did we record any

specific bending response in our nail specimens dependent of the orientation of the specimen's long axis in relation to the main fibre orientation of the nail plate (Fig. 1). The macromolecular organization of nail keratin, the dorsal plate and the cellular architecture of the nail cross-section (cf. 2 and 4) are the structural bases for an understanding of this behaviour.

After unloading, the main quick return was followed by a very slow recovery phase which required more than 17 hours to regain the initial state. This means that, of several phenomena, at least an elastic and viscous phase can be identified (Fig. 3). The form of the recovery curve with respect to time suggests that the unloading viscosity is greater than the loading one. The fact that several molecular mechanisms are involved in the deformation pro-

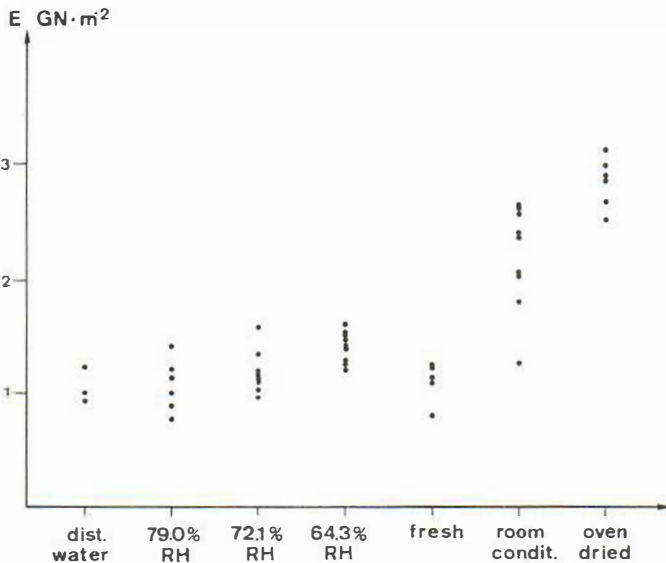


Fig. 6. Effective elastic modulus, E_{eff} , dependence on water content of the specimen.

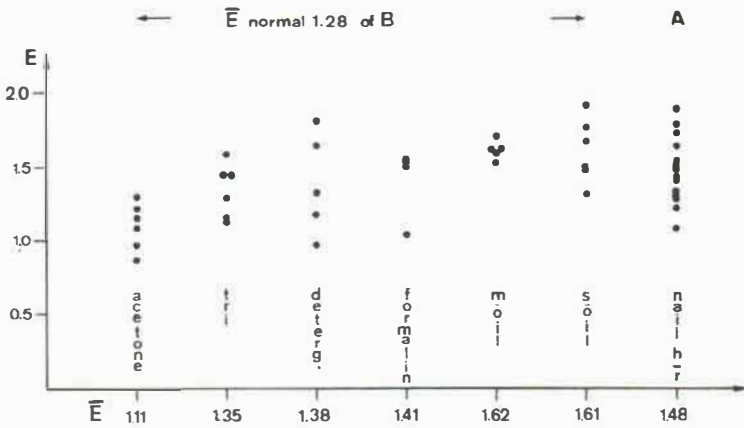


Fig. 7. E_{eff} dependence on previous treatment of nail with organic solvents, tensides, mineral (*m*-) and vegetable (*s*-) oils as well as a commercial 'nail hardener'.

cess is evident from the constant load experiments (Fig. 4). The loading viscosity is most probably the sum of several viscous phenomena. Among possible effects the movement of keratin filaments in the non-structured matrix of the intracellular compartment is one of importance.

The proteins of the intermembranous substance will also contribute to the viscosity of the material. These protein or muco-polysaccharide-proteins are probably random coils. At loading, orientation of the cellular structure in the direction of the applied stress will occur and the random coils will be stretched. A certain degree of memory will be retained in these stretched molecules and the return to a random coil will be recorded as an increased degree of viscosity.

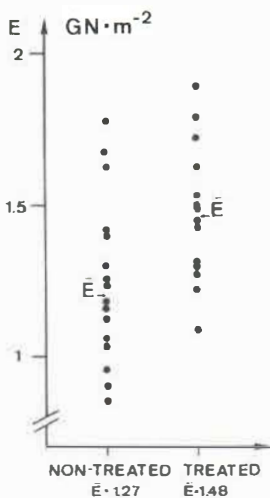


Fig. 8. The change in E_{eff} after treatment of fingernails with a commercial 'nail hardener' for 6 weeks.

Studies using indentation methods to measure 'hardness' in nails have failed to account for the fact that the nail substance exhibits viscous flow at loading (6, 9) as has been stressed by Newman & Young (7). The fact that the nail is plasticized to different degrees by its water content is an everyday experience and was also considered in experimental studies previously (1, 7, 8) as in the present study.

Thus it is the opinion of the present authors that 'hardness' is not a feasible definition for the property of withstanding bending and buckling in a composite organic material like that of the nail. We therefore propose that *rigidity* or *stiffness* be used in this context when a strict physical parameter such as the effective elastic modulus is not used.

In conclusion, the effective elastic modulus is a well defined mechanical property in this context, as the linear range of the load-deformation relationship is finite. We have shown that the nails, prior to stiffness measurements, must be well equilibrated as regards water content. Furthermore, a case history of a patient must be established so as to reveal contacts with detergents, organic solvents, oils, etc., factors which may affect the nail stiffness. With these facts in mind we are at present exploring methods for nail stiffness determination which are more sensitive than that presented here. Our aim is to make such a method directly applicable for clinical use in health and disease.

ACKNOWLEDGEMENTS

The present investigation was supported by a financial grant from Karolinska Institutets fonder.

The manufacture of our experimental set-up was possible through the excellent skill of Mr Lennart Wallerman.

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Received October 15, 1979

B. Forslind, M.D.
Department of Medical Biophysics
Karolinska Institutet
S-10401 Stockholm 60
Sweden